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NASA Geodynamics Program Summary Report: 1979–1987

Progress and Future Outlook

NASA Office of Space Science and Applications
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FOREWORD

Toward the end of the last decade, the NASA Geodynamics Program grew out of the efforts of many to use space technology as a means of acquiring information about the solid Earth. At that time, the use of precise Satellite Laser Ranging (SLR) and Very Long Baseline Interferometic (VLBI) techniques for distance measurements was advancing rapidly, but it would have required great foresight to predict the present achievement of measurement precision at the centimeter level. On the other hand, Lunar Laser Ranging (LLR), conceived as a global technique in the late 1960's, had not progressed as expected. Furthermore, the concept of spaceborne laser ranging had been set aside in deference to the promise of a "new" geodesy using radio signals from the Global Positioning System (GPS) satellites.

Gravity field modeling had advanced quickly, spurred on by the National Geodetic Satellite Program and new results from the GEOS-3 radar altimeter. The Seasat mission, although short-lived, provided even more accurate altimetric data which set the stage for yet another push towards improving knowledge of the gravity field, and particularly the ocean geoid. And, for the first time, a dedicated mission with the capability of producing an enormous advance in our knowledge of the gravity field appeared technologically and politically feasible. In addition, the Magnetic Field Satellite, Magsat (the first satellite dedicated to mapping the Earth's main and crustal magnetic fields), was in the final stages of preparation for launch.

Equally important, the technical achievements and the new data sources had led to an awareness in U.S. federal agencies, and in the international community, of the advent of a new era of geodesy and geodynamics - an era in which observations using space methods would provide vital information obtainable by no other means.

So it was in 1979 that NASA reorganized elements of the Earth and Oceans Applications Program and the Earth Science Program into the NASA Geodynamics Program. The eight years that have followed have seen major scientific and technological advancements towards the Program goals established in 1979. Naturally, not all that was planned has been achieved. However, most of the accomplishments of the Program have exceeded our original expectations. As the Program advanced and the scientific discipline matured, the goals have been redefined several times, toward greater accuracy, better resolution, better coverage of the globe, and wider participation of other countries, and there is continuing expectation of further significant results as the Geodynamics Program moves towards the decade of the 1990's.

Annual reports on the Program's progress were issued for 1979, 1980, 1981, 1982, and 1983 (NASA, 1980a; NASA, 1981; NASA, 1982d; NASA, 1983d; NASA, 1984e) and an overview of the Program was published in 1983 (NASA, 1983a). The present report, the Sixth Geodynamics Program Report, summarizes the Program's achievements from its initiation in 1979 through the end of calendar year 1987.

TABLE OF CONTENTS

I. EVOLUTION OF THE NASA GEODYNAMICS PROGRAM 1
A. STATUS OF RESEARCH IN THE 1970's 1
B. FEDERAL PROGRAM 3
C. INTERNATIONAL PROGRAM 3
D. PROGRAM OBJECTIVES 4
E. CRUSTAL DYNAMICS PROJECT 4
F. FUNDING 5

II. SCIENTIFIC RESULTS: 1979-1987 8
A. CRUSTAL DYNAMICS RESEARCH 8
1. Plate Motion and Plate Stability Results 20
2. Regional Deformation Results 26
B. EARTH ORIENTATION STUDIES 31
1. Earth Rotation: UT1 31
2. Polar Motion 40
3. Precession and Nutation 45
4. Project MERIT 47
C. GEOPOTENTIAL RESEARCH 47
1. Gravity Field 47
2. Geoid 50
3. Tidal Gravity Field 52
4. Main Magnetic Field 52
5. Crustal Magnetic Fields 57

III. SYSTEMS AND MODELING DEVELOPMENT 62
A. SATELLITE LASER RANGING 62
1. Permanent SLR Stations 62
a. Moblas Systems 62
b. SAO Systems 68
2. Transportable Laser Ranging Stations 68
a. TLRS-1 68
b. TLRS-2 70
c. TLRS-3 and -4 70
d. MTLRS-1 and-2 70
3. Lunar Laser Ranging 72
a. MLRS 73
b. Haleakala Observatory 73
c. Orroral Valley Facility 77
4. Future Developments 77
B. VERY LONG BASELINE INTERFEROMETRY 80
1. Observatory VLBI 81
2. Mobile VLBI 84
3. Tropospheric Calibrations and Modeling 88
4. VLBI Correlator Facilities 89
5. Technical Developments 89
C. GLOBAL POSITIONING SYSTEM 95
1. Background 95
2. Technology Development 95
3. System Tests and Field Experiments 96
4. Future Development 99

D. SPACE MISSIONS AND INSTRUMENTATION 99
1. Laser Geodynamics Satellite 99
2. Geodynamics Laser Ranging System 102
3. Geopotential Research Mission 102
4. Gravity Gradiometers 104
5. Magnetic Field Explorer 106
6. Tethered Satellite System 108
7. Shuttle Time and Frequency Transfer 108

IV. OUTLOOK 110
A. CRUSTAL DYNAMICS 110
1. Global Plate Motions 110
2. Plate Boundary Deformation 112
3. Intra-Plate Deformation 112
B. EARTH ORIENTATION STUDIES 113
C. GEOPOTENTIAL RESEARCH 114
1. Gravity Field and Geoid 114
2. Magnetic Fields 116
a. Main Field 116
b. Crustal Field 116

V. PROGRAM CHRONOLOGY: 1979-1987 120
A. 1979 - 1980 120
B. 1981 - 1982 121
C. 1983 - 1984 122
D. 1985 124
E. 1986 125
F. 1987 126

APPENDIX A Glossary of Acronyms and Abbreviations 129

APPENDIX B References 133

LIST OF FIGURES

Fig. I-1	Functional Diagram of the DIS	6
Fig. II-1	(a) Western Hemisphere SLR Baselines	9
Fig. II-1	(b) Eastern Hemisphere SLR Baseline	10
Fig. II-2	North American Laser Tracking Stations	14
Fig. II-3	North American, Pacific and Eurasian VLBI Baselines	15
Fig. II-4	(a) Western U.S. Regional Deformation VLBI Baselines, May, 1987	16
Fig. II-4	(b) Alaska-Canada VLBI Baselines: July - August, 1985	17
Fig. II-5	European and Mediterranean Area Laser Tracking Sites	21
Fig. II-6	Geodetic Measurements along the Northern Caribbean Plate Boundary	22
Fig. II-7	SLR Observed and Predicted Plate Motion Rates for the Pacific Basin	23
Fig. II-8	Horizontal Velocities of VLBI Stations in the Pacific Basin Using Data from 1984-1986	25
Fig. II-9	Geomorphic Provinces and Principal Faults of California	27
Fig. II-10	SLR Observed Plate Motion Rates for Western U.S. Compared with Predicted Values	28
Fig. II-11	Velocities of VLBI Sites in California and the Western U.S.: 1982-1987	30
Fig. II-12	Velocities of VLBI Sites in Alaska and Canada: 1984-1986	32
Fig. II-13	Atmospheric Angular Momentum Calculations	34
Fig. II-14	(a) Daily Axial Atmospheric Angular Momentum for 22 Equal Area Belts: Winter of 1982-1983	35
Fig. II-14	(b) Difference of Belt Angular Momentum for Winter of 1982-1983 with the Average for Four Winters Beginning in December, 1986	36
Fig. II-15	Comparison of Excess LOD with the Southern Oscillation Index	38
Fig. II-16	Lageos-I Nodal Residuals	39
Fig. II-17	Comparison of Polar Motion Data with Predicted Pole Position from Air Pressure Data	41
Fig. II-18	Kalman-Smoothed Geodetic vs. NMC Pressure Data	42
Fig. II-19	SLR- and VLBI-Determined Positions of the Pole	43
Fig. II-20	Differences in Lageos-Derived Earth Rotation Parameters	44
Fig. II-21	Residual Polar Nutation	46
Fig. II-22	Comparison of the "Quality" of Gravity Field Models: 1960-1987	48
Fig. II-23	Precision Orbit Computations for Starlette Using the May 1986 TOPEX Gravity Model	51
Fig. II-24	Global Mean Sea Level Surface Based on Seasat and Geos-3 Altimeter Data	53
Fig. II-25	Observed and Predicted Geoid	54
Fig. II-26	Crustal Scalar Magnetic Anomaly Map of Canada and Northern U.S.	59
Fig. II-27	Contour Map of the Magsat Field for the North Atlantic	60
Fig. III-1	Satellite Laser Ranging Stations: September 1987	63
Fig. III-2	Moblas Laser Station (Moblas-7)	67
Fig. III-3	Transportable Laser Ranging Station (TLRS-1)	69
Fig. III-4	Modular Transportable Laser Ranging Station (MTLRS-1)	71
Fig. III-5	Improvement in LLR Data Quality	74
Fig. III-6	McDonald Laser Ranging Station (MLRS)	75
Fig. III-7	Mt. Haleakala, Hawaii, Lunar Ranging Receiver Telescope	78
Fig. III-8	Mojave, California, VLBI Station	82

Fig. III-9	Fairbanks, Alaska, VLBI Station	83
Fig. III-10	Mobile VLBI Station (MV-1)	85
Fig. III-11	Mobile VLBI Station (MV-2)	86
Fig. III-12	Mobile VLBI Station (MV-3)	87
Fig. III-13	J-Series Water Vapor Radiometer Instrument	90
Fig. III-14	Repeatability of GPS Measurements for the Loreto-Mazatlan Baseline	97
Fig. III-15	Range Residuals for a Single Rogue Receiver Observing a Single GPS Satellite	98
Fig. III-16	GPS Geodetic Network Planned for 1987-1989	100
Fig. III-17	Three-Axis Superconducting Gravity Gradiometer.	106
Fig. IV-1	Magnetic Anomaly Resolution as a Function of Satellite Altitude.	118
Fig. IV-2	Resolution of Magnetic Crustal Anomalies for Satellite Missions	119

LIST OF TABLES

Table I-1 Geodynamics Program Funding: FY 1979-1988 7
Table II-1 Global Network of Fixed Stations: 1984 - 1987 11
Table II-2 Location of Mobile System Sites: 1984 - 1987. 18
Table II-3 Second Degree Tidal Gravity Field Solution (GEM-T1) 55
Table III-1 Comparison of SLR System Design Features. 64
Table III-2 Precision for Single-Shot Laser Ranging 65
Table III-3 McDonald and Haleakala Station Design Features 76
Table III-4 Baseline Ranging Repeatability (VLBI) 91
Table III-5 (a) VLBI Baseline Measurement Error Analysis (400 km Baselines). . . .93
Table III-5 (b) VLBI Baseline Measurement Error Analysis (4000 km Baselines) . . .94
Table IV-1 High-Priority Site Locations 111

I. EVOLUTION OF THE NASA GEODYNAMICS PROGRAM

A. STATUS OF RESEARCH IN THE 1970's

The use of satellites for geodesy was one of the earliest applications of space technology. Indeed, the determination of the figure of the Earth and the discovery of large errors in the location of points on the surface of the Earth were among the first revelations of the infant Space Program. The following chronology is summarized in Section V.

In the early 1960's, at the direction of the U.S. Congress, NASA led the formation of the National Geodetic Satellite Program (NGSP), which incorporated the requirements of several other Federal agencies. The NGSP was responsible for the early geodetic satellites, such as the Army-Navy-NASA-Air Force (ANNA) satellites, the Beacon Explorers, and the initial Geodetic Satellite (GEOS) series (later, for GEOS-3, the name was changed to Geodynamic Experimental Ocean Satellite). Concurrent with the satellite program, experimentation on laser tracking of satellites and the development of interferometric methods for position determination using astronomical radio sources led to the realization that these techniques had the potential to advance the precision of long-baseline geodetic measurements by several orders of magnitude.

The Williamstown Conference of 1969 (NASA, 1969), was convened to discuss exploiting these new capabilities. This Conference, a major milestone in satellite and space geodesy, was the first attempt to formulate information needs and establish scientific objectives and requirements for studies of the solid Earth. In response to these needs, NASA created the Earth and Ocean Physics Application Program (EOPAP) in 1972.

EOPAP gave birth to satellite programs such as: the Geodynamics Experimental Ocean Satellite (GEOS-3); the Laser Geodynamics Satellite (Lageos-I); Seasat; and later, the Magnetic Field Satellite (Magsat). EOPAP also established accuracy goals for position determination and measurements of polar motion and Earth rotation. In the decade and a half which has followed, all of these missions have flown and the measurement accuracy goals have been exceeded. However, while the contributions of GEOS-3 and Seasat to the definition of the Earth's gravity field and ocean geoid were reasonably well understood before launch, the impact of these missions in revealing unknown features on the ocean bottom and in advancing understanding of ocean tectonics was not anticipated.

The development of Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Lunar Laser Ranging (LLR) continued during the 1970's through research efforts such as the San Andreas Fault Experiment (SAFE): a program to measure the change in baseline length between two distant points on opposite sides of the fault; the Pacific Plate Motion Experiment (PPME), which used fixed and mobile VLBI systems to measure plate motion; and the Lunar Ranging Experiment (LURE).

By 1979, the development of these technologies had advanced to a level which made extensive application to global research practical. This led to the formulation of the current NASA Geodynamics Program. The objectives and plans of the new Program (NASA, 1979a) evolved from the Williamstown Conference, the EOPAP, the views of the scientific community, the projected capabilities of ground and space techniques, and the needs of other Federal agencies.

While, at the time, there was only a hint of plate motion determination in the SAFE results, direct observations of global plate motion were deemed sufficiently important to advances in tectonophysics to be included as a major objective of the Geodynamics program. This was valid since the SLR and VLBI techniques were the only foreseeable means of making direct observations of that motion. Furthermore, earthquake research, awakened abruptly in the mid-1970's because of concern for a major earthquake associated with the San Andreas Fault system, focused on crustal deformation as one of the two most likely indicators of precursory activity (the other being animal behavior). Questions as to the accumulation and release of crustal strain resulting from plate motion and the degree of rigidity of plate interiors were paramount. The nature of plate motion itself, whether steady or episodic, and the mechanism of the driving forces were speculative. Equally speculative was the possibility of coupling between the Earth's rotational dynamics and the seismic energy released by major earthquakes. Thus, the mapping of large-scale crustal strain in the western U.S. and Alaska was readily identifiable as a task of great importance to U.S. earthquake research. Crustal extension of the stable cratonic interior of the North American Plate, believed from geological data to be less than one centimeter per year, remained as a possible source for intraplate earthquakes such as those in the New Madrid (Missouri) area. Thus, the degree of stability or rigidity of tectonic plates was also an important question.

The Earth's global gravity field, having been reasonably well defined using data acquired during the NGSP and by the GEOS-3 and Lageos-I missions, was thought to be known to an accuracy of eight milligal with a resolution of 800 km (half wavelength). These gravity field models, while interesting and of value for some applications, still lacked the accuracy and resolution needed to study lithospheric structures, subduction zones, mantle convection, or mid-ocean ridges. Thus, improvements to the gravity field models were made a primary objective of the NASA program. The gravity field measurement requirements were examined by the Committee on Earth Sciences of the Space Science Board, National Research Council, in 1979 (NAS, 1979), and expanded upon by a NASA Gravity Field Users Working Group in 1980 (NASA, 1980). These requirements, and the studies that followed, resulted in the development of the Gravity Field Satellite (Gravsat) concept (later renamed Geopotential Research Mission - GRM) which would use satellite-to-satellite tracking to measure the gravity field to an accuracy of a few milligals and a half-wavelength resolution of about 150 km.

In the 1970's the Earth's interior structure and the dynamics of the inner core had been extensively studied using seismology and analyses of polar motion, but a full understanding consistent with physical laws was still elusive. Except for some earlier satellite measurements of the global magnetic field, magnetic field models in the late 1970's were derived from sparsely distributed, ground-based magnetic observatories. Thus, frequent satellite surveys of the magnetic field to study field changes and to ascertain both the effects of core/mantle dynamics and perhaps the origin of the Earth's field were incorporated into the Program. Magsat was the first satellite dedicated to this purpose.

These same requirements for studies of the interior dynamics and structure of the Earth led to efforts to improve the spatial precision and time resolution of measurements of polar motion and Earth rotation.

B. FEDERAL PROGRAM

Interagency coordination in the use of space for research and applications in the geosciences has been a mainstay of these programs since the early 1960's. The successful NGSP, concluded in 1974 (NASA, 1977), was a good example of interagency coordination. Thus, in the formulation of the NASA Geodynamics Program, it was natural to begin with the informal creation of a consortium of agencies to help define the program and to integrate their interests. This informal interagency coordinating committee first met in mid-1979; it consisted of program-level representatives from NASA, the U.S. Geological Survey of the Department of the Interior (USGS/DOI), the National Geodetic Survey of the National Oceanic and Atmospheric Administration (NGS/NOAA), the National Science Foundation (NSF), and the Defense Mapping Agency of the Department of Defense (DMA/DOD). The committee members agreed (NASA et al., 1979a) that space technology had valuable contributions to make to geodetic and geophysical sciences, and that a method of coordinating related activities in the different agencies should be established. This resulted in the implementation of a formal agreement among these five agencies in September 1980. This agreement established the objectives for the Federal program, outlined the roles and responsibilities of each Agency, formalized an Interagency Coordinating Committee for Geodynamics (ICCG), and established a Program Review Board of senior Agency managers to oversee the Program. The ICCG was charged with the issuance and maintenance of a Federal Program Implementation Plan. The first of these plans was issued in June 1982 (ICCG, 1982).

In 1962, a Geodetic Satellite Program Board (GSPB) had been formed under the NGSP with membership from NASA, NOAA, and DMA. The GSPB was renamed the Satellite Geodesy Applications Board (SGAB) in 1979, and in 1982 it was combined with the Geodynamics Program Review Board.

C. INTERNATIONAL PROGRAM

International cooperation in solid Earth research was extensive in the NGSP and continued during the GEOS-3, Seasat, and Lageos-I missions. Indeed, the plan for the NASA Geodynamics Program (NASA, 1979b) included global studies involving many countries, and predicted the participation of many other countries - everywhere that regional tectonic movement was of practical or scientific importance. Other countries have participated in various ways: as hosts for NASA-provided and operated systems, through investigators analyzing data provided by NASA and in joint observations using national systems. International scientific investigations for NASA's Lageos-I and Magsat missions and the Crustal Dynamics Project (CDP) were submitted in response to Announcements of Opportunity (AO), and investigators from some fourteen countries were selected. Eighteen countries are participating by acquiring SLR, LLR, and/or VLBI data with national systems or systems provided on loan from NASA. To date, twenty-two countries are, or have been, involved in the NASA Program. As a result of the CDP AO, the European scientific community formed a consortium of selected NASA investigators to study crustal deformation in the Mediterranean. This "Working Group of European Geoscientists for the Establishment of Networks for Earthquake Research (WEGENER) Consortium", which includes several Mediterranean and middle East countries, has established a precedent for regional international cooperation in geodynamical space studies. Another important example of effective international coordination in geodynamical research was the IAU-sponsored program for Monitoring of Earth Rotation and Intercomparison of Techniques (MERIT).

D. PROGRAM OBJECTIVES

The goals of the NASA Geodynamics Program are:

- o To contribute to the understanding of the solid Earth, in particular, the processes that result in movement and deformation of the tectonic plates;
- o To obtain measurements of the Earth's rotational dynamics and its gravity and magnetic fields in order to better understand the internal dynamics of the Earth.

The Geodynamics Program is subdivided into three areas: Earth Dynamics, Crustal Motion, and Geopotential Research.

The objectives of the Earth Dynamics Program are to develop models of polar motion and Earth rotation and to relate studies of global plate motion to the dynamics of the Earth's interior. This program is expected to lead to an increased understanding of the global structure of the Earth and the evolution of the crust and lithosphere. The research conducted in this Program includes studies of the dynamic interaction between different regions of the Earth's tectonic features. A significant portion of this Program element includes activities performed under the CDP, through highly accurate measurements of Earth rotation and polar motion.

Field measurements and modeling studies of crustal deformation in various tectonic settings are the primary focus of the Crustal Motion Program. These activities provide measurements, analyses, and models which describe the accumulation and release of crustal strain and the crustal motion between and within the tectonic plates, particularly the North American, Pacific, Eurasian, South American, and Australian plates. Activities include development of quantitative descriptions of geophysical and geological constraints on the motions of measuring sites, including refinements of global plate motion models and block tectonic models of the western U.S. The investigations also compare the geologically determined values to test the predictions of geological models.

The Geopotential Research Program uses space and ground measurements to construct gravity and magnetic field models while investigating data analysis techniques and software systems. Studies of the Lageos-I orbit and the orbits of near-Earth satellites are part of the efforts directed toward advancing gravity field studies. Data used in constructing the models include gravity field data derived from satellite altimetry, satellite-to-satellite tracking, and gravity gradiometry; magnetic field data from satellite magnetometers; and ancillary data.

E. CRUSTAL DYNAMICS PROJECT

The Crustal Dynamics Project (CDP), a major element of the NASA Geodynamics Program, was formed in 1979 under the management of GSFC. The objectives and plans for the CDP were derived from the NASA Geodynamics Program Plan (NASA, 1979b). The scientific objectives of the CDP are to improve knowledge and understanding of:

1. Regional deformation and strain accumulation related to large earthquakes in

plate boundary regions in western North America;

2. The present relative motions of the North American, Pacific,South American, Nazca, Eurasian, and Australian Plates;

3. Internal deformation of continental and oceanic lithospheric plates, with particular emphasis on North America and the Pacific;

4. Rotational dynamics of the Earth and their possible correlation with earthquakes, plate motion, and other geophysical phenomena;

5. Regional deformation in other areas of high earthquake activity.

The initial CDP Project Plan extended through 1986, and included measurements of: (1) regional deformation in western North America, South America, the Caribbean, the eastern Mediterranean, and New Zealand; (2) global plate motion and internal stability of the plates; and (3) polar motion and Earth rotation. Due to budget limitations in 1982 and 1983, completion of the CDP was extended to 1988 and the South American, Caribbean, and New Zealand studies were deleted. Later, in 1984, the Caribbean studies were re-initiated at the direction of the U.S. Congress as a Global Positioning System (GPS)-based research program and the program was assigned to JPL. In 1985, as a result of continued budgetary limitations, the duration of the CDP was extended to 1991.

The CDP is responsible for the development of SLR, LLR, and VLBI systems and for the acquisition, processing and archival of geodetic baseline, Earth rotation, and polar motion data acquired by NASA systems or provided to NASA through cooperative agreements and international programs.

As part of its data management, the CDP has designed and implemented a centralized Data Information System (DIS). The system is described in Figure I-1. The DIS has been fully operational since September, 1982. The main purpose of the DIS is to store all geodetic data products acquired by the CDP in a central data bank and to maintain information about the archival of all CDP-related data. Authorized CDP investigators have access to the DIS by means of a dial-up telephone line.

The CDP investigators and Federal agency scientists form the CDP Principal Investigator's Working Group, which meets semi-annually to discuss investigator results and to review CDP status and progress.

F. FUNDING

Funding from all sources for the Geodynamics Program from its inception in Fiscal Years 1980 to 1988 is shown in Table I-1.

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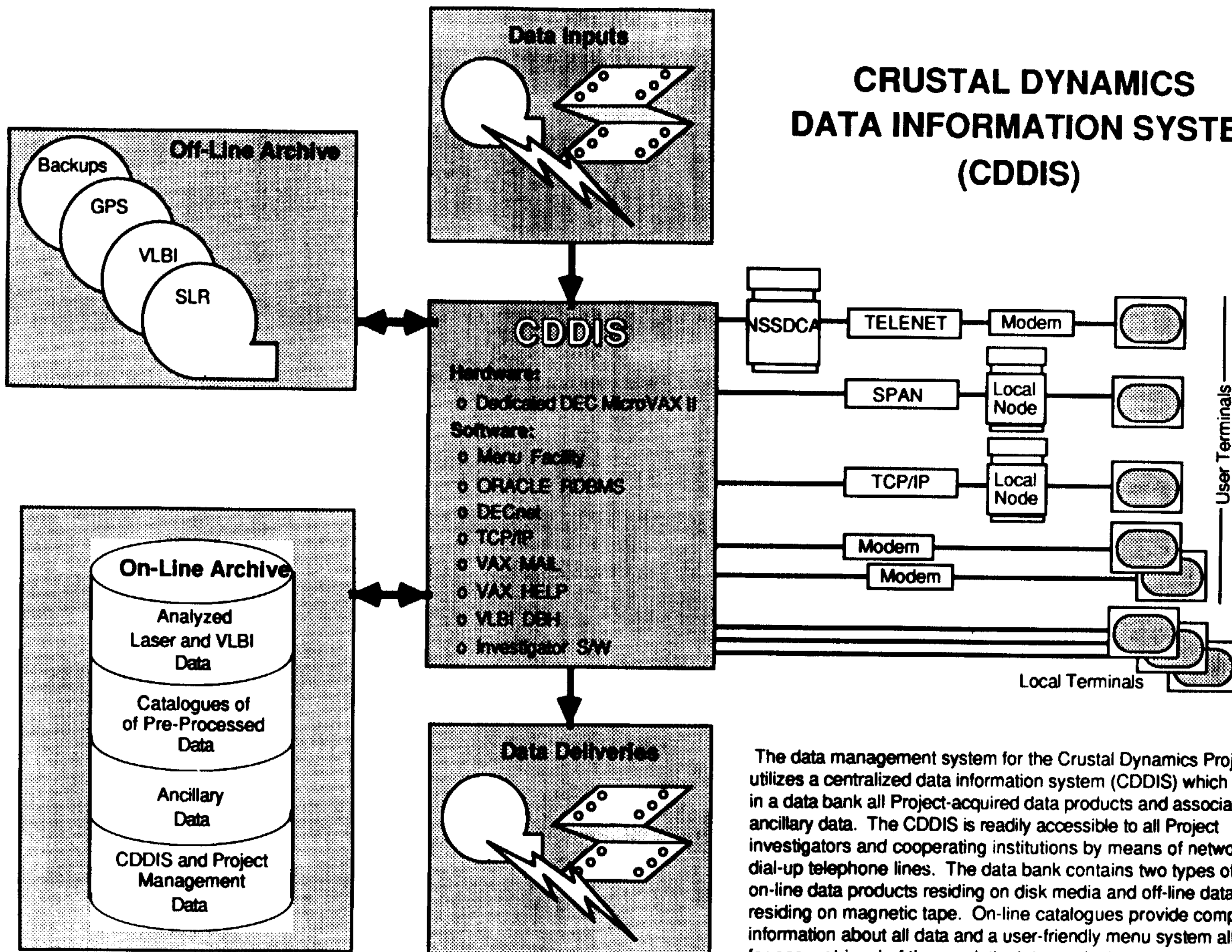
CRUSTAL DYNAMICS DATA INFORMATION SYSTEM (CDDIS)



The data management system for the Crustal Dynamics Project utilizes a centralized data information system (CDDIS) which stores in a data bank all Project-acquired data products and associated ancillary data. The CDDIS is readily accessible to all Project investigators and cooperating institutions by means of network or dial-up telephone lines. The data bank contains two types of data: on-line data products residing on disk media and off-line data residing on magnetic tape. On-line catalogues provide complete information about all data and a user-friendly menu system allows for easy retrieval of the geodetic data products.

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Figure I-1 Functional diagram of the Data Information System (DIS).

TABLE I-1

GEODYNAMICS PROGRAM FUNDING BY FISCAL YEAR

Fiscal Year	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988
Funding (millions)	16.6	25.3	27.1	23.7	27.1	29.9	29.9	30.0	32.1	33.1

II. SCIENTIFIC RESULTS: 1979-1987

A. CRUSTAL DYNAMICS RESEARCH

To meet its objectives, the CDP, building on measurements obtained by predecessor programs since 1972, has been actively measuring present relative plate motion, internal plate stability, and regional crustal deformation for the past eight years. Frequent measurements of baselines among many stations in active areas near plate boundaries are being made to determine regional deformation and strain accumulation. Baselines among a global set of stations are being measured repeatedly to determine relative plate motions. Repeated measurements of baselines between several stations on the same plate are being made to determine the internal deformation of the plate.

Direct measurements of plate motion and crustal deformation require geodetic systems capable of measuring long baselines (100-10,000 km) over any terrain with very high accuracy (at least one part in 10^8). VLBI and SLR have the capability required for measuring plate motions, crustal deformation, and small changes in the Earth's orientation and rotation.

The ultimate accuracy of the baseline measurements depends on the level of systematic biases. Since the SLR and VLBI systems have very different error sources and biases, direct comparison of measurements on the same baselines is a good method for uncovering these problems. Based on comparisons already conducted, the SLR and VLBI baseline measurements agree with each other within the combined uncertainties of the individual systems. This indicates that the systematic errors are not larger than the random errors for the SLR and VLBI systems (Kolenkiewicz et al., 1985). Comparison with GPS measurements has begun, but several more years of data will be needed to eliminate or reduce error sources for long baselines. From 1979 to 1987, the CDP has improved the precision of the SLR and VLBI systems from 10 cm to 1 cm. With this precision, repeated measurements made over periods of many years will yield velocity determinations at the level of a few millimeters per year.

Table II-1 lists the global network of fixed stations operating in 1987. The network consists of stations operated by the CDP plus stations owned and/or controlled by other groups and cooperating with NASA under special agreements. The operation of this network requires the participation and cooperation of a large number of organizations both in the U.S. and in other countries.

The basic philosophy for the network has been to establish, where possible, at least three stations on the stable part of each plate to measure internal plate deformation and to serve as a reference network for measurements of relative plate motions. These same stations also serve as reference base stations for measurements of regional deformation with mobile stations near active plate boundaries.

Figures II-1(a) and II-1(b) show the baselines along which measurements are routinely being made by SLR stations located around the world. This network also provides tracking data for the precision orbit determination for the retroreflector satellites and the Moon. The global SLR network is configured for emphasis on plate motion measurements between the North American, Pacific, Nazca, South American, and Australian

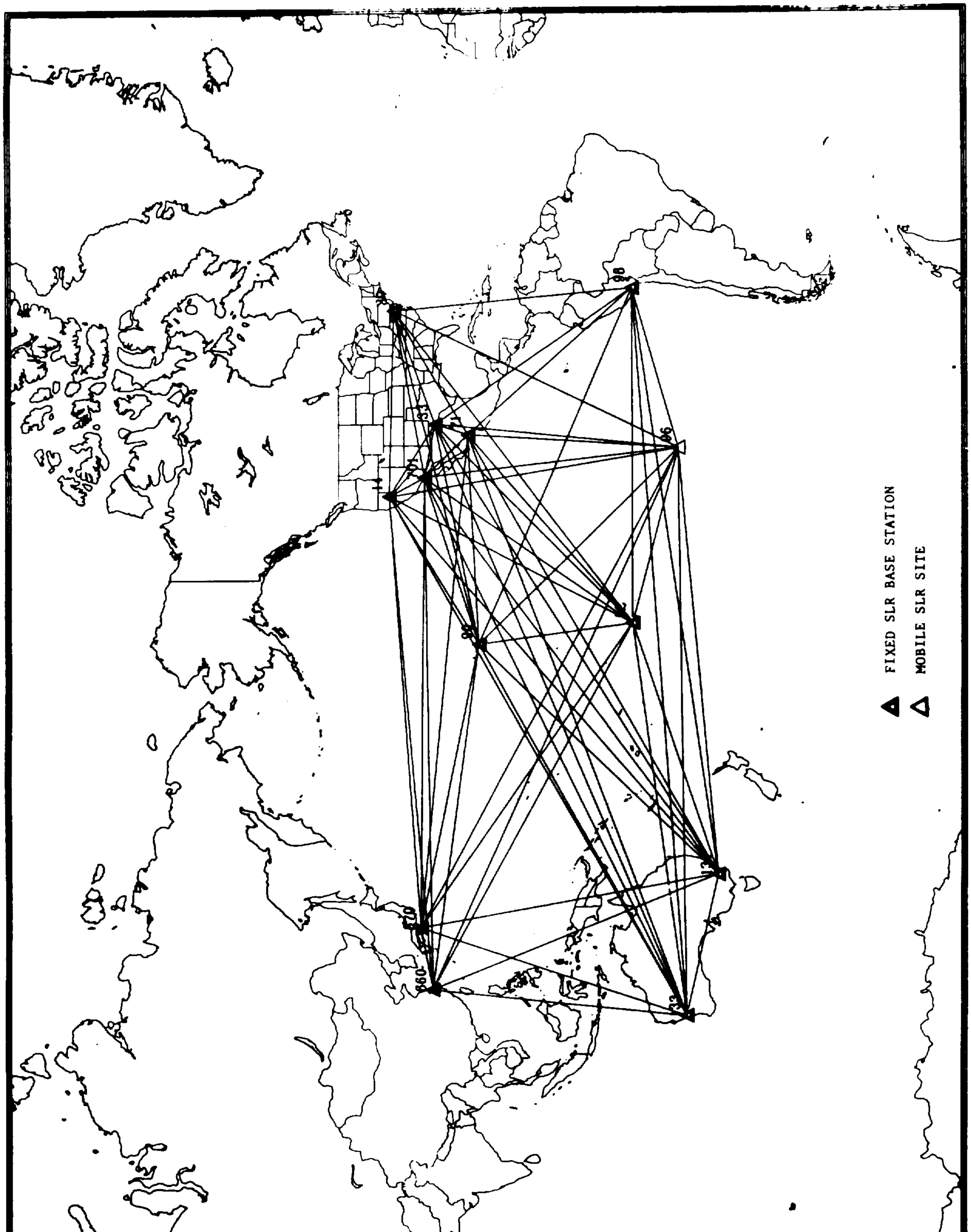

Figure II-1(a) Crustal Dynamics Project - SLR baselines in the western hemisphere.

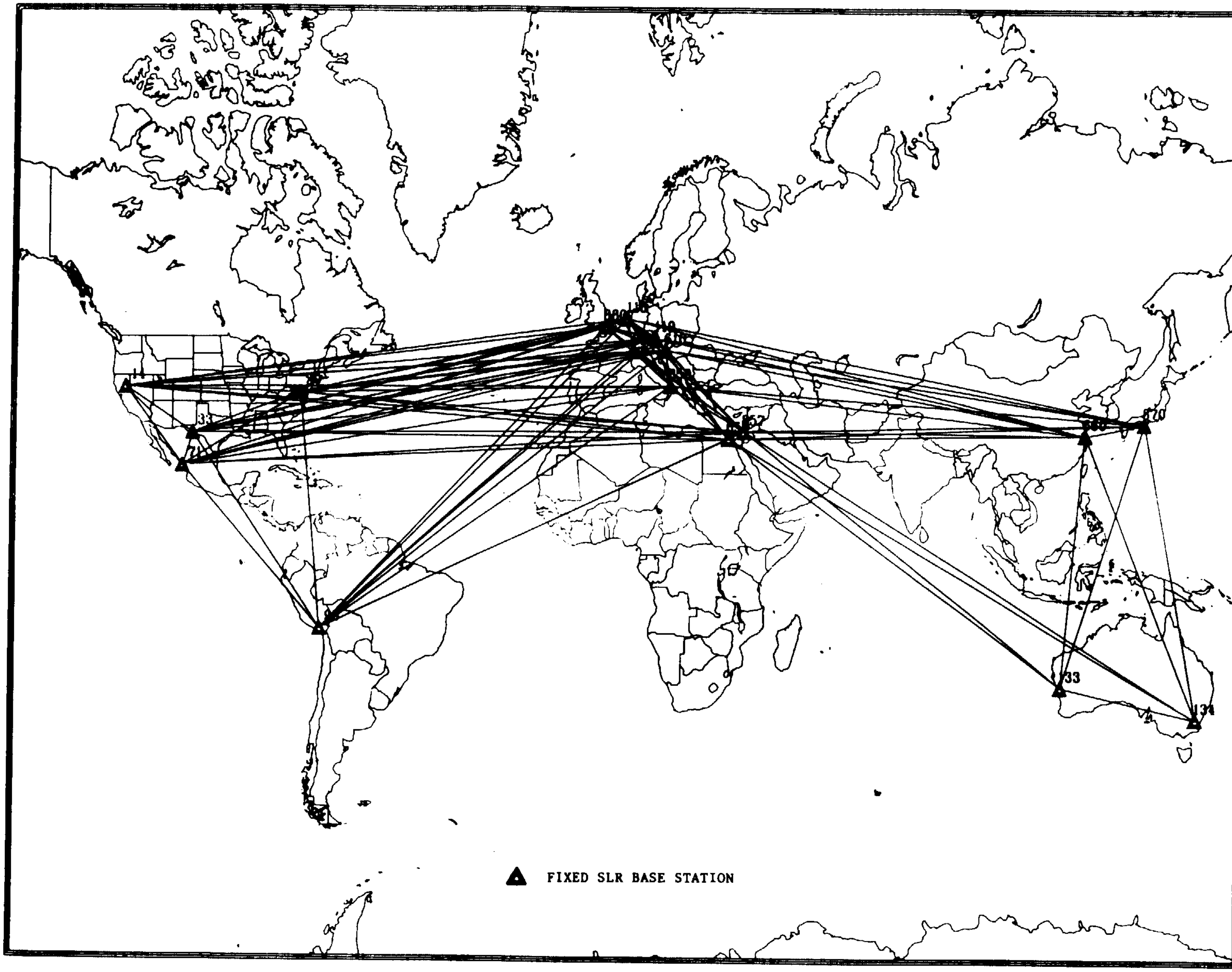

Figure II-1(b) Crustal Dynamics Project - SLR baselines in the eastern hemisphere.

TABLE II-1

SLR/LLR/VLBI NETWORK: FIXED STATIONS

1984 - 1987

LOCATION	SYSTEM	ORGANIZATION
NORTH AMERICAN PLATE		
GREENBELT, MARYLAND	MOB. 7	CDP
QUINCY, CALIFORNIA	MOB. 8	CDP
MAZATLAN, MEXICO	MOB. 6	CDP
FT. DAVIS, TEXAS	MLRS	UTX
FT. DAVIS, TEXAS	VLBI/POLARIS	NGS/HARVARD
MOJAVE, CALIFORNIA	VLBI	NGS
OWENS VALLEY, CALIFORNIA	VLBI	CIT/CDP
HAT CREEK, CALIFORNIA	VLBI	UCB/CDP
WESTFORD, MASSACHUSETTS	VLBI/POLARIS	NGS
WESTFORD, MASSACHUSETTS	VLBI	HAYSTACK OBS.
RICHMOND, FLORIDA	VLBI/POLARIS	USNO
MARYLAND POINT, MARYLAND	VLBI	NRL
FAIRBANKS, ALASKA	VLBI	CDP
PACIFIC PLATE		
MONUMENT PEAK, CALIFORNIA	MOB. 4	CDP
VANDENBERG AFB, CALIFORNIA	VLBI	NGS
MT. HALEAKALA, HAWAII	SLR/LLR	U. HAWAII/CDP
HUAHINE IS., FRENCH POLYNESIA	TLRS-2	CDP
KAUAI, HAWAII	VLBI	NASA-STDN/CDP
KWAJALEIN ATOLL, MARSHALL IS.	VLBI	US ARMY/CDP
SOUTH AMERICAN PLATE		
AREQUIPPA, PERU	SAO-2	CDP
NAZCA PLATE		
EASTER ISLAND	TLRS-2	CDP
AUSTRALIAN PLATE		
YARRAGADEE, AUSTRALIA	MOB. 5	CDP
ORRORAL VALLEY, AUSTRALIA	SLR/LLR	SURVEY MAPPING GP.

TABLE II-1 Continued

LOCATION	SYSTEM	ORGANIZATION
EURASIAN PLATE		
SIMOSATO, JAPAN	SLR	DEPT. SCIENCE TECH.
KASHIMA, JAPAN	VLBI	RADIO RESEARCH LAB.
SHANGHAI, CHINA	SLR/VLBI	SHANGHAI OBSERVATORY
WETTZELL, FRG	SLR/VLBI	INST. F. ANGEWANDTE GEODASIE
KOOTWIJK, NETHERLANDS	SLR	TECH. HOGES. DELFT
MATERA, ITALY	SAO-1	CONS. NAZ. RECHERCHE
GRASSE, FRANCE	SLR/VLBI	CNES
GRAS, AUSTRIA	SLR	INST. F. WELTRAUM-FORSCHUNG
HERSTMONCEAUX, ENGLAND	SLR	ROYAL GREENWICH OBS.
ZIMMERWALD, SWITZERLAND	SLR	INST. F.. GEODASIE
DIONYSOS, GREECE	SLR	NAT. TECH. UNIV.
ONSALA, SWEDEN	VLBI	CHALMERS INST. TECH.
BONN, FRG	VLBI	MAX PLANCK INST.
MEDICINA, ITALY	VLBI	INST. RADIO ASTRON.
ARABIAN PLATE		
BAR GIYYORA, ISRAEL	MOB. 2	ISRAEL SPACE AGENCY

Plates and for overlapping plate motion measurements with the VLBI Network between the North American, Pacific, and Eurasian Plates. Most of the global SLR stations are fixed stations. The exceptions are the sites at Huahine, French Polynesia; Easter Island; Santiago, Chile; and Cerro Tololo, Chile. These sites are occupied for periods of several months by Transportable Laser Ranging Systems (TLRS) for measurements of Nazca-South American-Pacific Plate motions.

The laser sites in North America are shown in Figure II-2. The measurements of crustal movements along the San Andreas Fault were initiated in 1972 between Quincy and Otay Mountain, California. These measurements are being continued by the CDP. In addition, the SLR base station on Monument Peak, near Otay Mountain, is making continuous measurements with Quincy. The addition of the base station at Mazatlan, Mexico, in 1983 and occupation of the mobile sites at Cabo San Lucas and at the southern tip of Baja California (in 1984) extended these measurements southward to include the spreading motion in the Gulf of California.

Figure II-3 shows the locations of the global fixed VLBI sites. Prior to 1984, only the continental U.S. and European sites existed. Starting in 1984, the North American stations conducted measurements with Pacific stations in Hawaii and Kwajalein, Marshall Islands; and stations in Japan, Sweden, and Germany. These baseline measurements contributed to the determination of the relative plate motion among the North American, Pacific, and Eurasian Plates, and the stability of the three Plates.

Table II-2 lists the locations of sites implemented for measurements with the highly mobile systems. Some of the locations are at or near fixed SLR or VLBI locations. The purpose of this is to permit duplicate measurements of some baselines with both SLR and VLBI systems in order to check for systematic errors in both systems.

Figure II-4(a) shows the baselines measured with mobile VLBI systems in 1987 for study of regional deformation in the western U.S. In order to achieve geometrical strength and redundancy, measurements are made with groups of stations. The minimum number in the group is three, but generally four or more are used. There are five base stations located at a distance from the San Andreas Fault zone and two highly mobile VLBI stations, MV-2 and MV-3, occupy many sites throughout the area. Each measurement is made with both MV-2 and MV-3 working with two to four base stations, resulting in 6 to 15 baseline determinations. Most sites are occupied once a year, but some sites in active regions are reoccupied several times a year. Since the base stations participate in each mobile measurements group, the baselines between the base stations are measured very frequently. As a consequence, their positions are the most accurately determined. These base stations then become the reference points to which all measurements are tied.

Figure II-4(b) shows the VLBI baseline measurements for the Alaskan campaign which started in 1984. The MV-2 and MV-3 systems occupied sites in Alaska for studies of regional deformation in that area of high earthquake activity. The base stations working with the mobile systems were Fairbanks, Alaska; Hat Creek, California; and Vandenberg, California.

The fixed stations and mobile sites in North America and the Pacific are completed and the emphasis is now on repeated measurements. Most of the European stations are operating: VLBI stations at Matera, Italy; Canberra, Australia; and Madrid, Spain are expected to be established in the future. Two Australian SLR stations are operating.

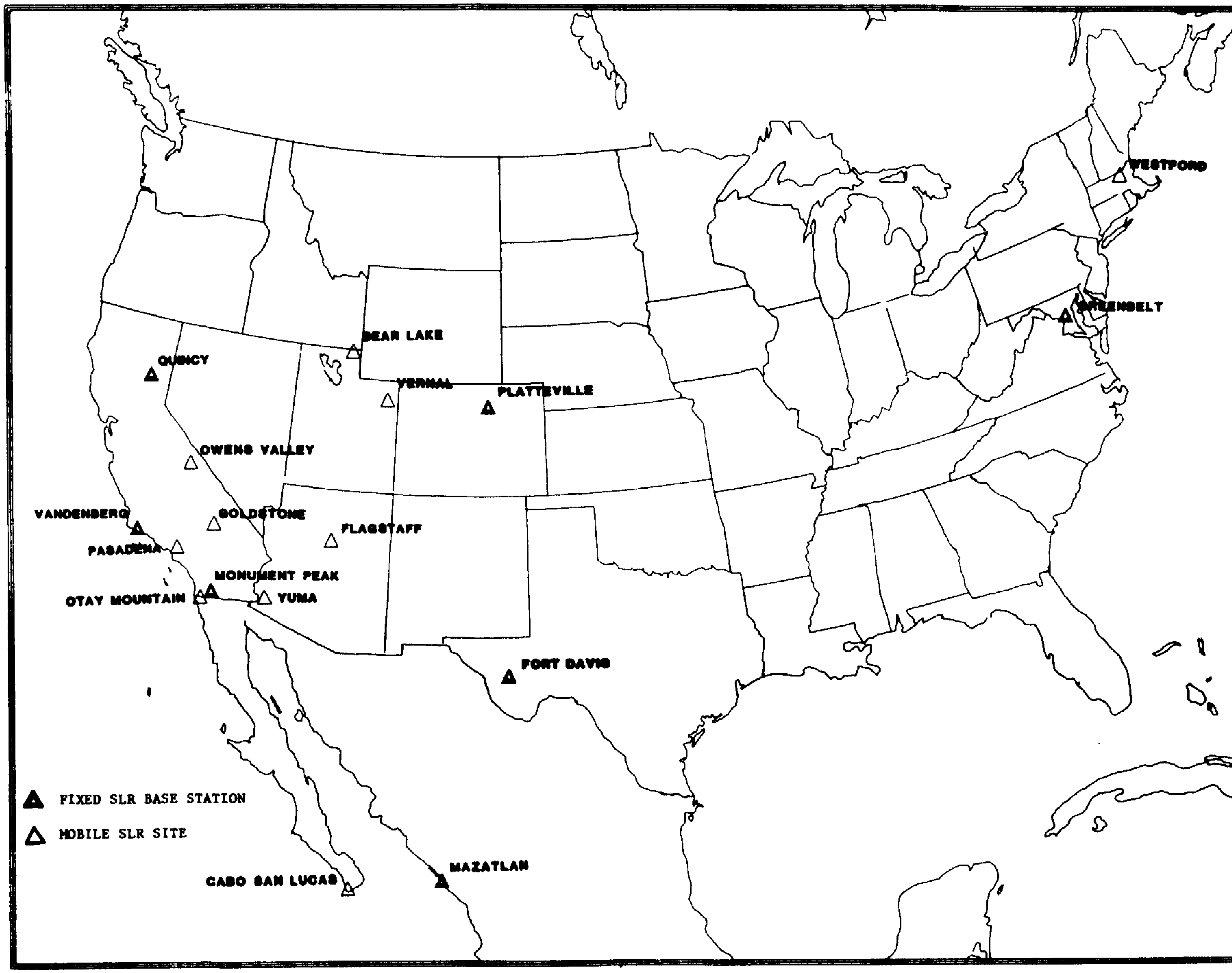

Figure II-2 North American laser tracking sites.

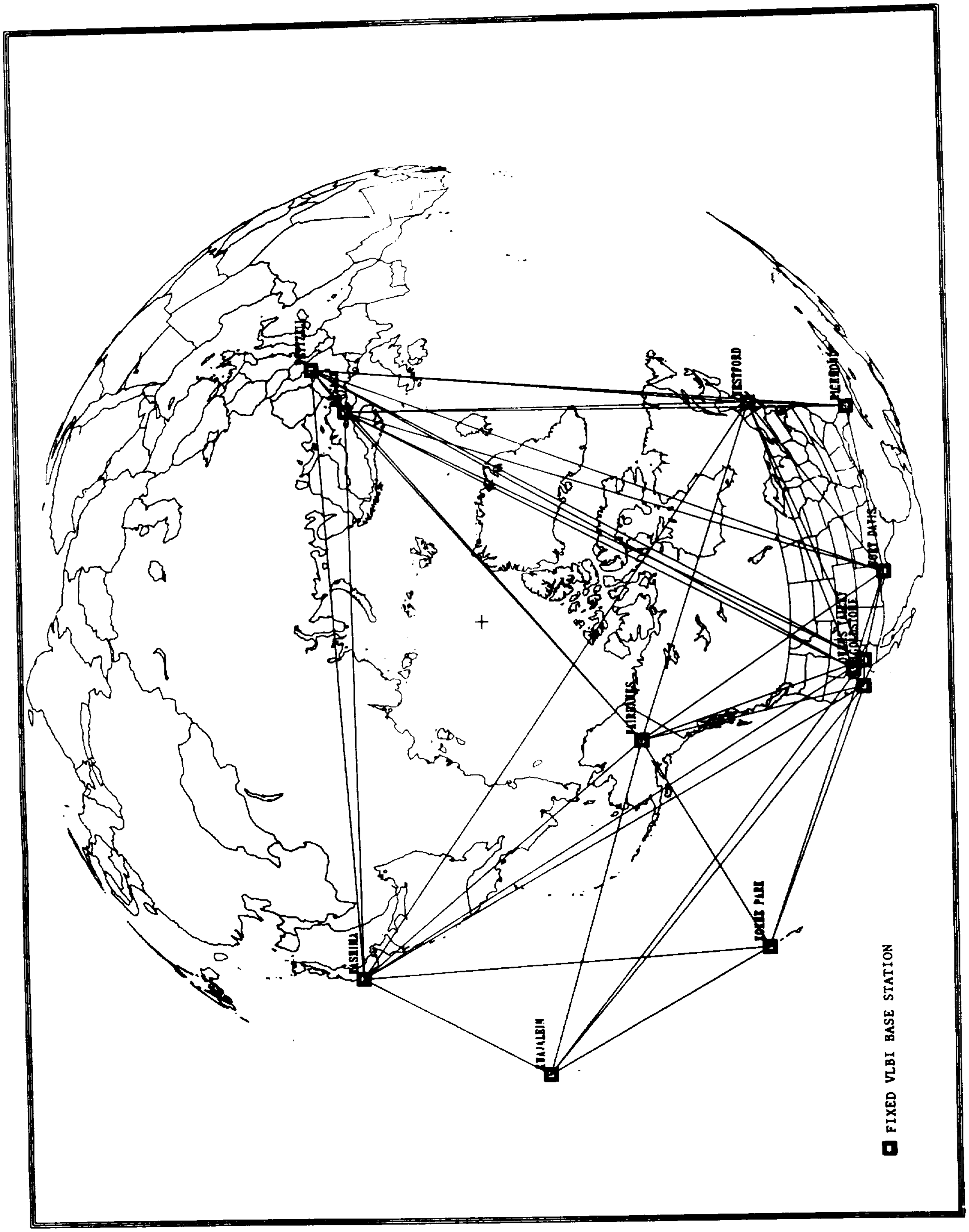

Figure II-3 North American, Pacific, and Eurasian VLBI baselines.

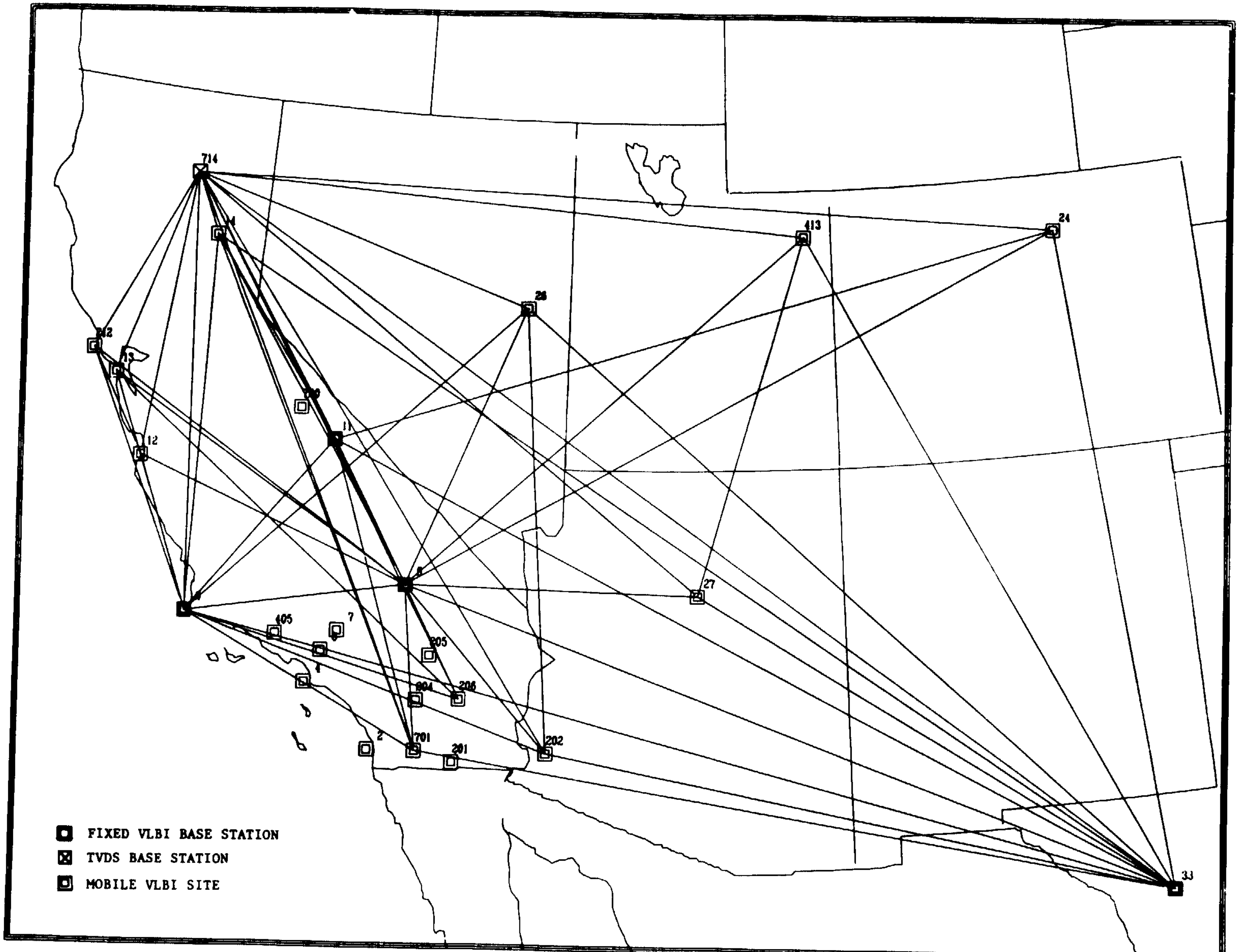

Figure II-4(a) CDP Baselines measured by VLBI in May 1987 for study of regional deformation in the western U.S.

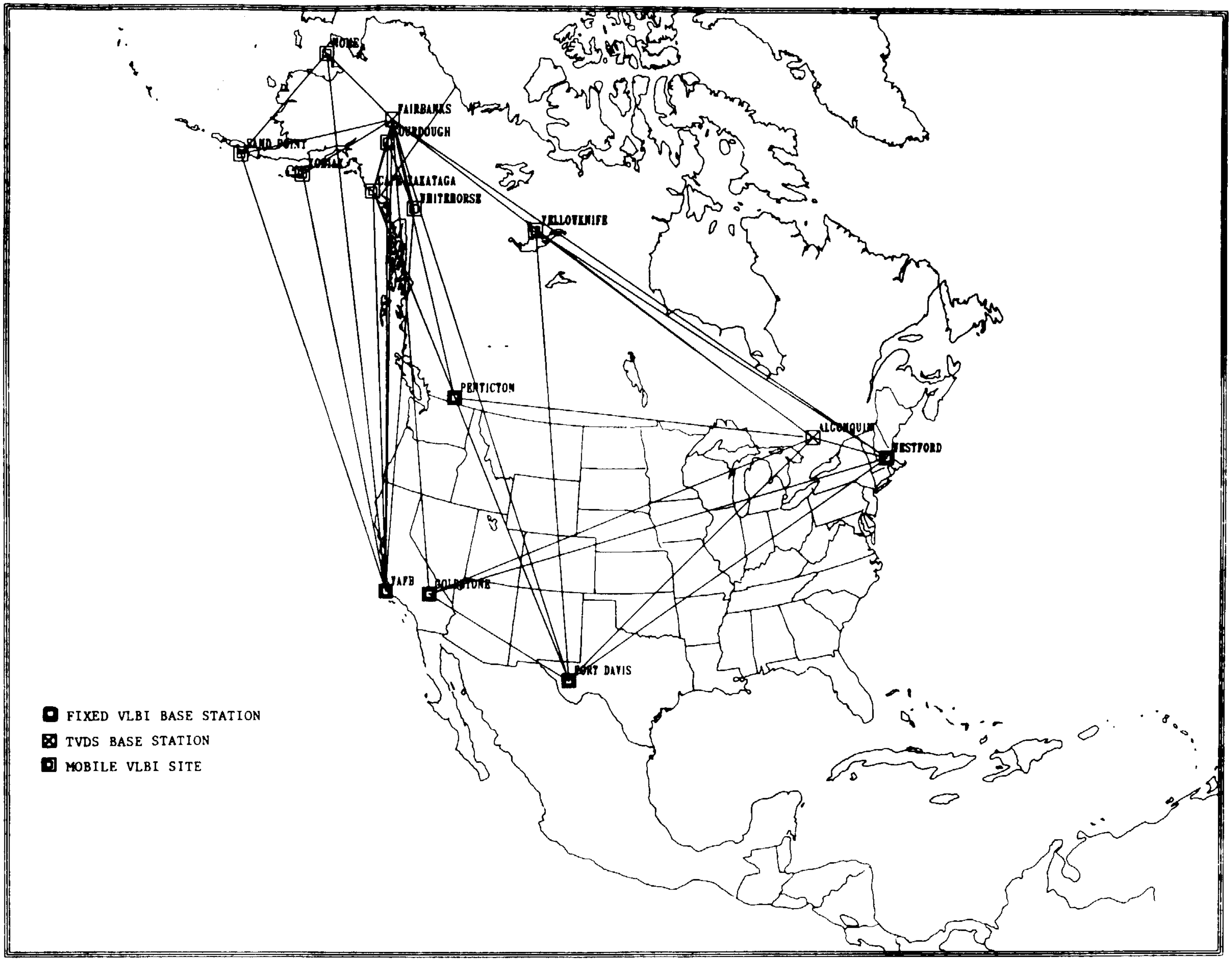

Figure II-4(b) Baselines measured in the Alaskan VLBI campaign in August 1985.

TABLE II-2

SITES FOR HIGHLY MOBILE SLR AND VLBI SYSTEM MEASUREMENTS, 1984 - 1987

LOCATION	PRIMARY HIGHLY MOBILE SYSTEM TYPE	FIXED STATION AT LOCATION
UNITED STATES		
Black Butte, California	VLBI/SLR	
Deadman Lake, California	VLBI	
Fort Ord, California	VLBI	
Pasadena, California	VLBI/SLR	
La Jolla, California	VLBI	
Mamouth Lakes, California	VLBI	
Monument Peak, California	VLBI	SLR
Mojave Desert, California	SLR	VLBI
Ocotillo, California	VLBI	
Otay Mountain, California	SLR	
Owens Valley, California	SLR	
Pinyon Flats, California	VLBI	
Pear Blossom, California	VLBI	
The Presidio, California	VLBI	
Point Reyes, California	VLBI	
Palos Verdes, California	VLBI	
Quincy, California	VLBI	SLR
Santa Paula, California	VLBI	
Kodiak, Alaska	VLBI	
Nome, Alaska	VLBI	
Sand Point, Alaska	VLBI	
Sourdough, Alaska	VLBI	
Cape Yakataga, Alaska	VLBI	
Flagstaff, Arizona	VLBI/SLR	
Yuma, Arizona	VLBI/SLR	
Plattsville, Colorado	VLBI/SLR	
Greenbelt, Maryland	SLR	SLR

TABLE II-2 Continued

LOCATION	PRIMARY HIGHLY MOBILE SYSTEM TYPE	FIXED STATION AT LOCATION
Westford, Massachusetts	SLR	VLBI
Ely, Nevada	VLBI	
Bear Lake, Utah	SLR	
Vernal, Utah	VLBI	
Canada		
Penticton	VLBI	
Whitehorse	VLBI	
Yellowknife	VLBI	
Mexico		
Ensinada	SLR	
Cabo San Lucas	SLR	
Chile		
Cerro Tololo	SLR	
Iquique	SLR	
Santiago	SLR	

New SLR and VLBI stations have begun operations in Japan. China has started operations of SLR and VLBI stations, and an agreement has been signed with Saudi Arabia for NASA cooperation in the implementation of SLR and VLBI stations on the Arabian Plate.

Prior to 1986, there were no NASA measurements of regional deformation anywhere outside of North America. The first measurements in support of the JPL Caribbean Research Program were made using GPS in 1986, and CDP participation in measurement of regional crustal deformation in the Mediterranean began in the same year.

The Mediterranean Laser (Medlas) Project was organized by the WEGENER Consortium. The Project plan calls for the use of a mixture of NASA and European fixed and mobile SLR systems for measurements of crustal motion in the Mediterranean. The SLR base stations are located in: Wettzell, Federal Republic of Germany (FRG); Graz, Austria; Matera, Italy; Herstmonceux, Great Britain; Zimmerwald, Switzerland; Dionysos, Greece; and Bar Giyyora, Israel. The Medlas measurements began in 1986 using Modular Transportable Laser Ranging Systems (MTLRS-1 and MTLRS-2). In 1987, these systems were joined in Europe by TLRS-1. The sites occupied in 1986 and 1987 are shown in Figure II-5. TLRS-1 returned to the U.S. at the end of 1987, and will be joined by MTLRS-1 for a series of measurement campaigns in the U.S. in 1988. The WEGENER Medlas measurements will be repeated in 1989 and 1991.

The Caribbean studies will use GPS receivers to attempt detection of the motion of the Caribbean Plate relative to the North American, South American, and Cocos Plates. Initial measurements in 1986 (Figure II-6) were limited to studies of the Northern boundary of the Caribbean Plate. In early 1988, measurements were made in the Western Caribbean and northern Andean South America. These measurements will include sites in Costa Rica, Columbia, Ecuador, Venezuela, and several islands.

1. Plate Motion and Plate Stability Results

The conclusion which can be drawn from the analysis of SLR and VLBI measurements from 1979 through 1987 is that the movement of the plates has been confirmed; the motions generally agree in magnitude and direction with the average movements over millions of years as inferred from geological evidence.

Baselines across the Pacific calculated using the latest SLR solution are compared in Figure II-7 with values determined using the Minster-Jordan model (1978). The SL7.1 solution for the locations of the SLR stations uses the GEM-T1 gravity, Earth and ocean tide force models, and the Wahr nutation model in the J2000 reference system. It also includes the effects of eclipses by the moon on the effects of solar radiation pressure. The a priori Earth orientation parameters and UT1 used were derived from the SL7.0 solution. Thus, the SL7.1 solution is a completely independent consistent solution for station positions and Earth orientation parameters.

Least-squares solutions for monthly (thirty or thirty-five day) orbital arcs of SLR data to the LAGEOS-I orbit were computed with the GEODYN-II program. In the monthly arcs, adjustments were made for two coefficients of solar radiation pressure and two coefficients of the drag parameter. The positions for the SLR stations were then determined on an annual basis by combining the 12 monthly arcs (for 1976 the solution is May through December, and for 1987 the solution is January through June). The reference system in the annual solutions for 1976 through 1977 was defined by con-

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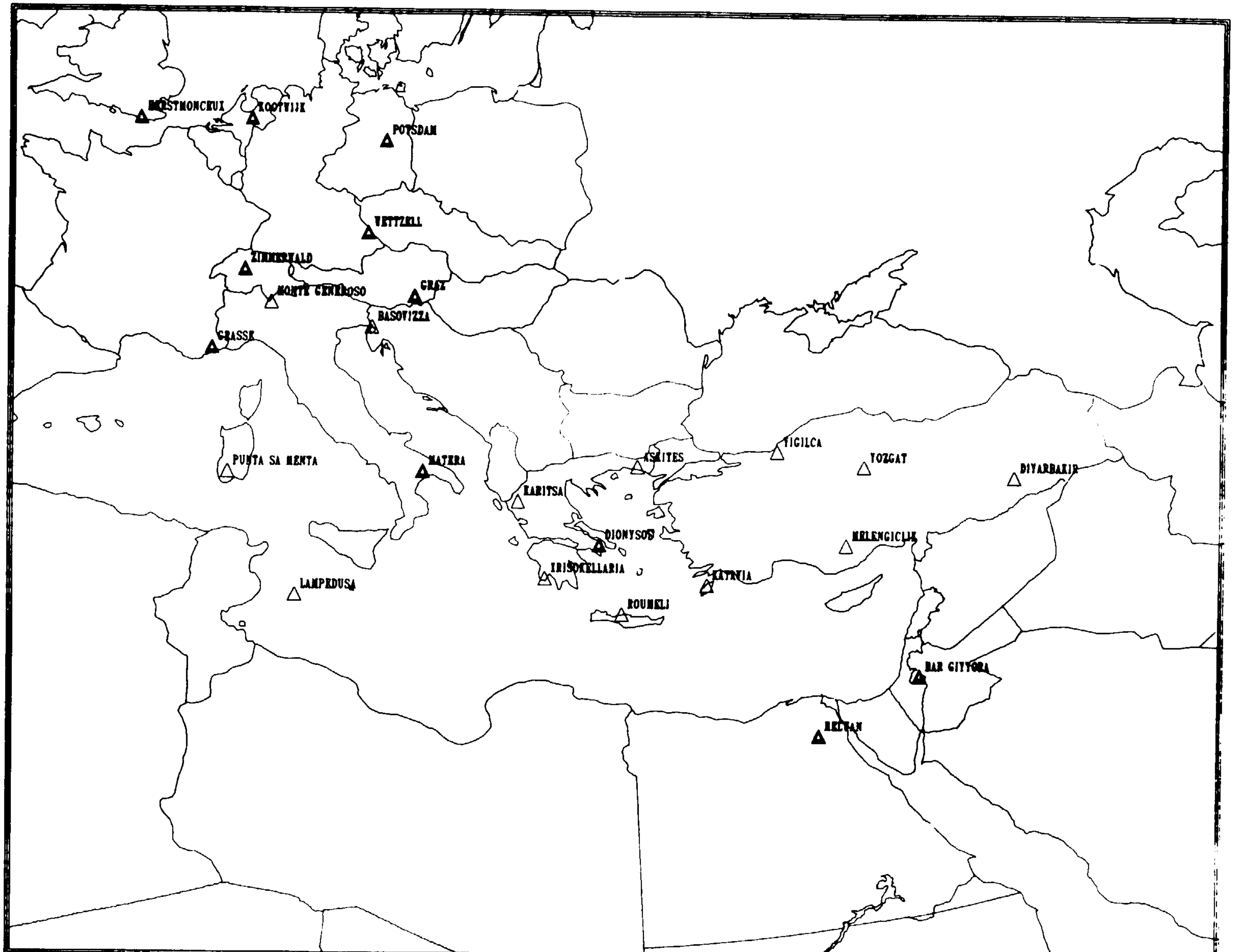

Figure II-5 European and Mediterranean area laser tracking sites occupied in 1985 and 1986.

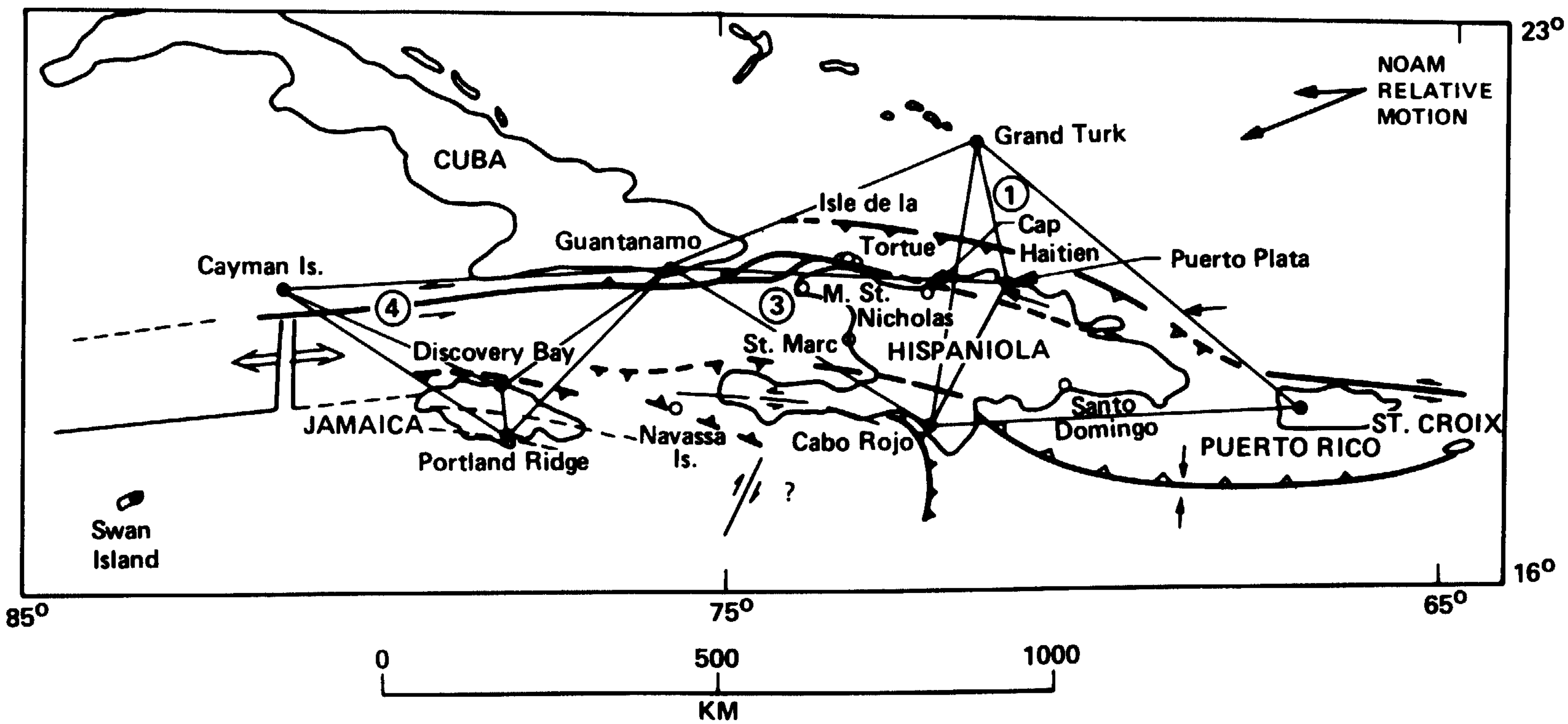

Figure II-6 Initial baselines measured in the 1986 GPS Caribbean campaign.

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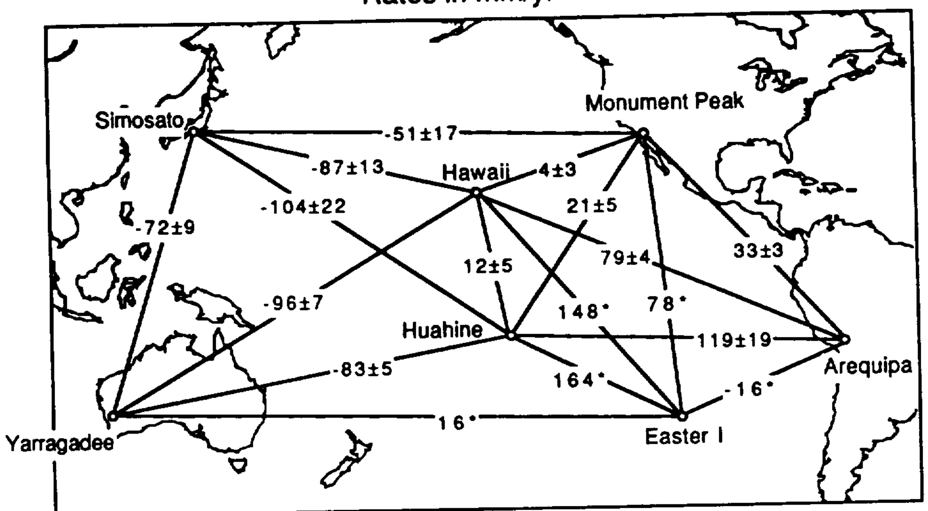
Observed

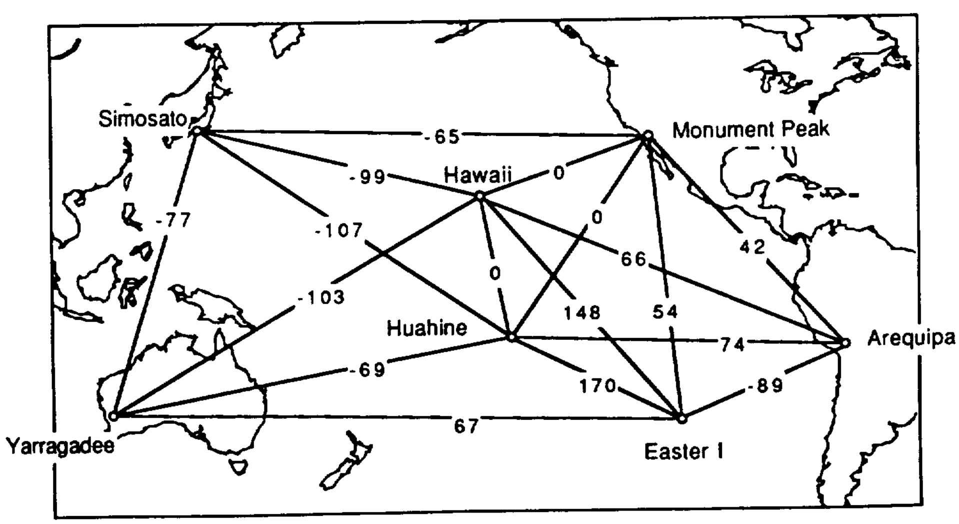
Rates in mm/yr



* Rates from Easter Island based upon two years of data.

Predicted

Rates in mm/yr



SL7.1 solution 871026

Figure II-7 Baselines across the Pacific calculated using the latest SLR solution (observed) compared with values determined using the Minster-Jordan model (predicted).

straining the latitude and longitude of Greenbelt, Maryland, and the longitude of Arequipa, Peru, to have motions as defined by the Minster-Jordan AM0-2 tectonic model (1978). The reference system in the annual solutions for 1978 through 1987 was defined by constraining the latitude and longitude of Greenbelt, Maryland and the latitude of Haleakala, Hawaii.

There are 105 baselines which have been determined at least four times between 1976 and 1987. Of these baselines, 45 have a precision of better than 10 mm/yr in the rate of change of the baseline length. An interesting aspect of this solution are the degree to which it agrees or disagrees with existing tectonic motion models. Generally the sites which measure global tectonic motion show excellent agreement with the tectonic motions predicted by AM0-2 and NUVEL-1, but are not yet precise enough to reveal differences between the models. Motion between the Pacific and Australian Plates has been observed by using the sites in Hawaii and Huahine on the Pacific Plate and Yarragadee, Australia. The observed rate of change of the baseline between Yarragadee and Hawaii is -96 ± 7 mm/yr compared to the AM0-2 rate of -103 mm/yr, and the observed baseline length change between Yarragadee and Huahine is -83 ± 5 mm/yr compared to the AM0-2 rate of -69 mm/yr. There are some intriguing differences between model predictions - in particular, the motion of Simosato, Japan, as observed in the SL7.1 solution is 15 mm/yr at an azimuth of 57^{o} instead of 28 mm/yr at an azimuth of 123^{o} (the expected motion if Simosato is on the Eurasian Plate) as predicted by AM0-2. This northeastern motion is inconsistent with Simosato being on either the Eurasian Plate or the Pacific Plate and probably implies regional deformation near the triple junction located in south central Japan.

Figure II-8 shows the horizontal velocities of the VLBI stations in and around the Pacific Basin estimated using data acquired from the Great Atlantic and Pacific Experiment (GAPE) campaigns in the period 1984-1986 (Ryan, 1987). The velocities are in a reference frame defined by fixing the positions of Fairbanks, Alaska, and Westford, Massachusetts.

Although, on average, the measured motions between plates appear to agree with those predicted by Minster and Jordan, there is a good deal of variability in the individual measurements which contribute to the averages. At this stage, the effects of local measurement errors cannot be dismissed, nor on the other hand, is it certain that these variations are not real.

It is anticipated that a minimum of five to six years of continuous observations is needed in order to obtain unambiguous estimates of the overall tectonic velocities: for a satisfactory assessment of the detailed nature of the movements, however (especially whether they are smoothly varying or episodic), even longer records will be necessary.

The stability of the North American Plate has been studied for almost a decade using VLBI sites. Analysis of these measurements show that the continent is essentially rigid (4 ± 1 mm/year) between the East and the West coasts (Ryan and Ma, 1987). While this result is not entirely surprising (extension of about one centimeter per year is implied by seismotectonic studies of the Basin and Range Province), it leaves unanswered the question of why intraplate earthquakes occur. Data for studies of the stability of other plates, such as the Pacific and Australian Plates, are presently of insufficient duration to draw conclusions about the general rigidity of the plates. However, if the cratonic plate interiors are indeed demonstrated to be rigid on the time scales applicable here, this result would have strong implications for the study of plate driving mechanisms and

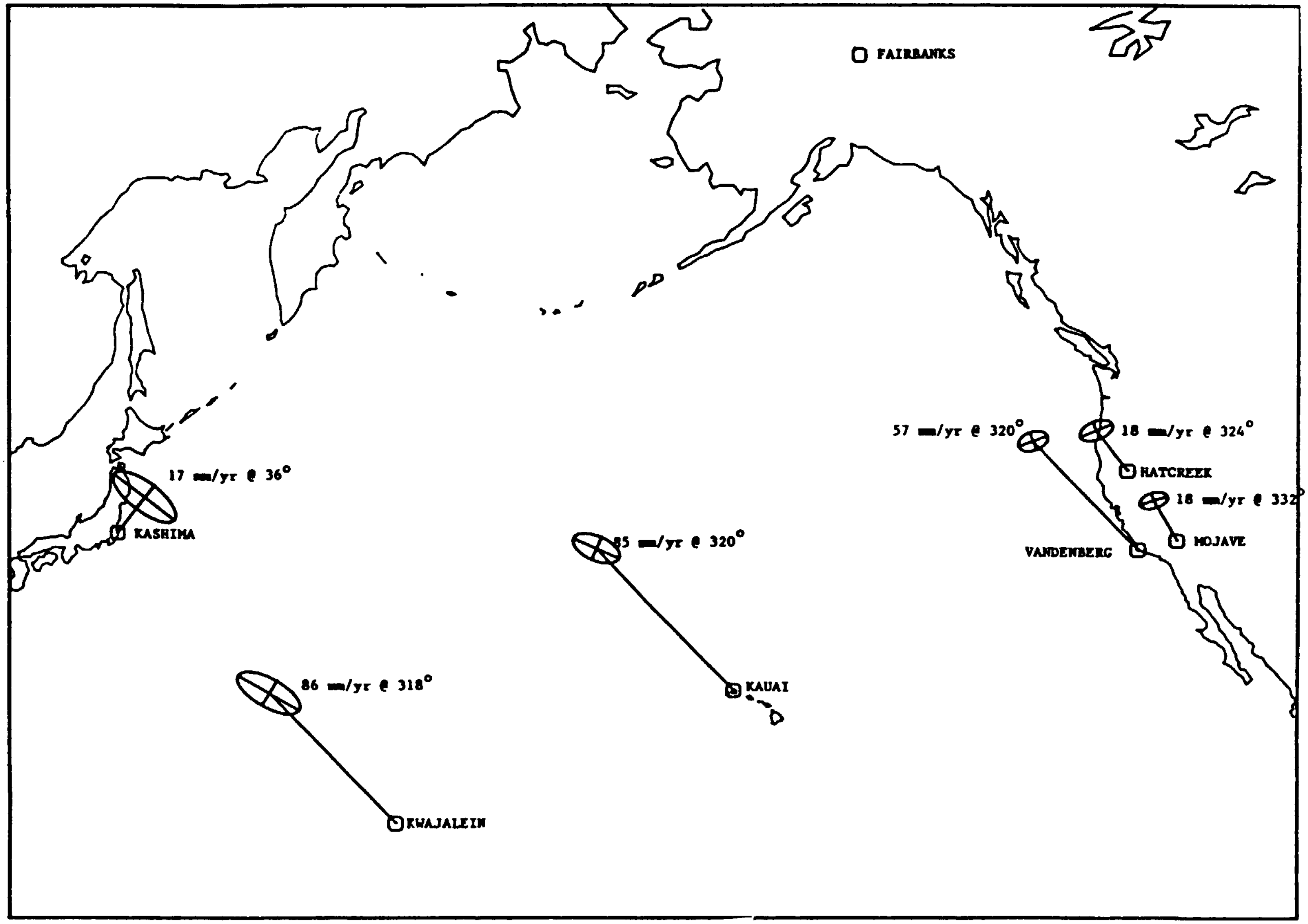


Figure II-8 Horizontal velocities of the VLBI stations in and around the Pacific Basin estimated using data acquired from the Great Atlantic and Pacific Experiment (GAPE) campaigns in the period 1984-1986.

deformation at plate boundaries.

2. Regional Deformation Results

The thirteen year history of SLR observations in the western U.S., and the more recent three-year history of extended mobile VLBI observations, clearly indicate that crustal deformation in southern California is more complex than suggested by simple fault-oriented models, and may involve broad-scale interactions and coupling between the upper and lower parts of the lithosphere, and between independently rigid tectonic blocks.

The longest period of tectonic motion measurements have been obtained by SAFE using SLR stations located at Quincy and Monument Peak in California. The setting for the SAFE baseline is shown in Figure II-9. The northern terminus is near Quincy in north central California. The southern terminus was originally at Otay Mountain, to the west of San Diego on the Pacific plate. The southern site was moved in 1981 (for logistical reasons) to Monument Peak, 50 km to the northeast near the Elsinore fault (but also on the Pacific plate). The early SLR observations from the sites which form the SAFE baseline were made to the Beacon Explorer-C. Since 1979, the majority of the observations have been made on Lageos-I.

The observed rates of motion for western North America (SL7.1 solution) are shown in Figure II-10. A persistent contraction of the SAFE baseline has been detected since the first resurvey in 1974. Over the years there have been significant improvements in the quality of the data and the modeling used to determine the station positions and baseline lengths. The current estimate of the rate of change in the length between the Quincy and Monument Peak sites in California, based on Lageos data from 1979 to 1986, is 26 ± 5 mm/yr. The contraction rate is less than that determined by VLBI techniques (i.e., 34 ± 6 mm/yr from Clark et al., 1987), although the difference is less than 10 mm/yr. More significantly, both results are less than the nearly 50 mm/yr required along this part of the plate boundary by rigid plate models. Implications can be drawn from this result in conjunction with the other observed motions between the SAFE sites and other sites on the North American and Pacific Plates. The observed extension rates for baselines terminating at Quincy, California, are: to Platteville, Colorado: 4 ± 11 mm/yr, to Greenbelt, Maryland: 6 ± 6 mm/yr, to McDonald Observatory, Texas: 10 ± 9 mm/yr, to Mazatlan, Mexico: 6 ± 14 mm/yr, and to Bear Lake, Utah: 19 ± 9 mm/yr. The extension rates to Bear Lake, Goddard, and Mazatlan are within one standard deviation of zero as would be required if Quincy were rigidly attached to North America. The measured lengths to McDonald are also consistent with little or no change if apparently anomalous data from 1979 is excluded from the analysis. Nevertheless, all of the values have positive means which suggests, albeit weakly, that Quincy is extending westward away from the interior of North America. This tendency is consistent with spreading in the Basin and Range. Observation of Basin and Range spreading is also consistent with VLBI observations in the western U.S. as reported by Clark et al. (1987).

SLR, VLBI, and conventional survey data also suggest that Monument Peak, California, is not rigidly attached to the Pacific Plate. The SAFE results, the observed motion across the Gulf of California to Mazatlan (i.e., 32 ± 8 mm/yr, which is less than the geological models would require), and the extension with respect to Tahiti (21 ± 4 mm/yr) support this view. The measured rate of extension to McDonald is also consistent with the nonrigid hypothesis (observed at 19 ± 2 mm/yr, compared to a rigid plate

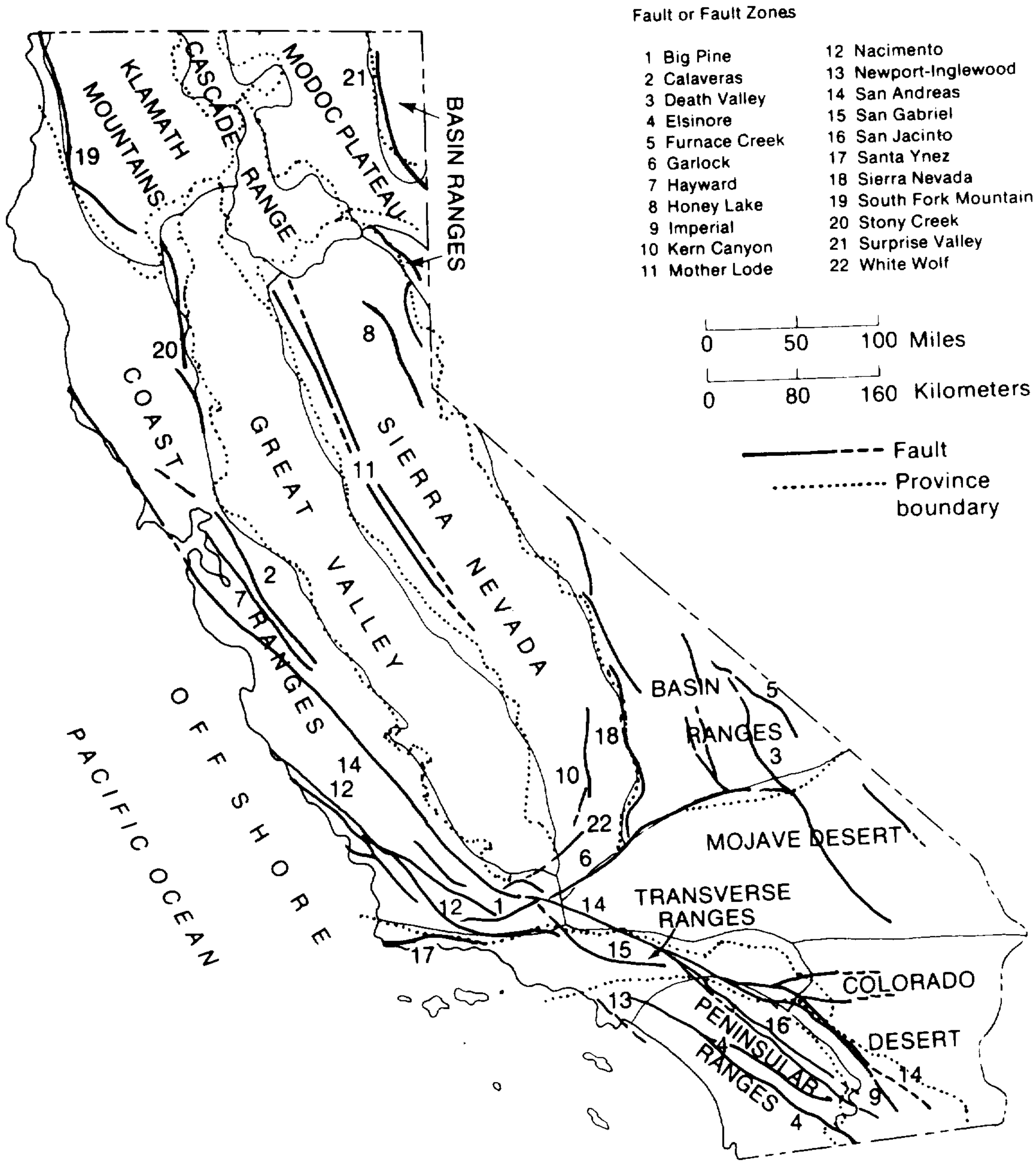


Figure II-9 Geomorphic provinces and principal faults in California.

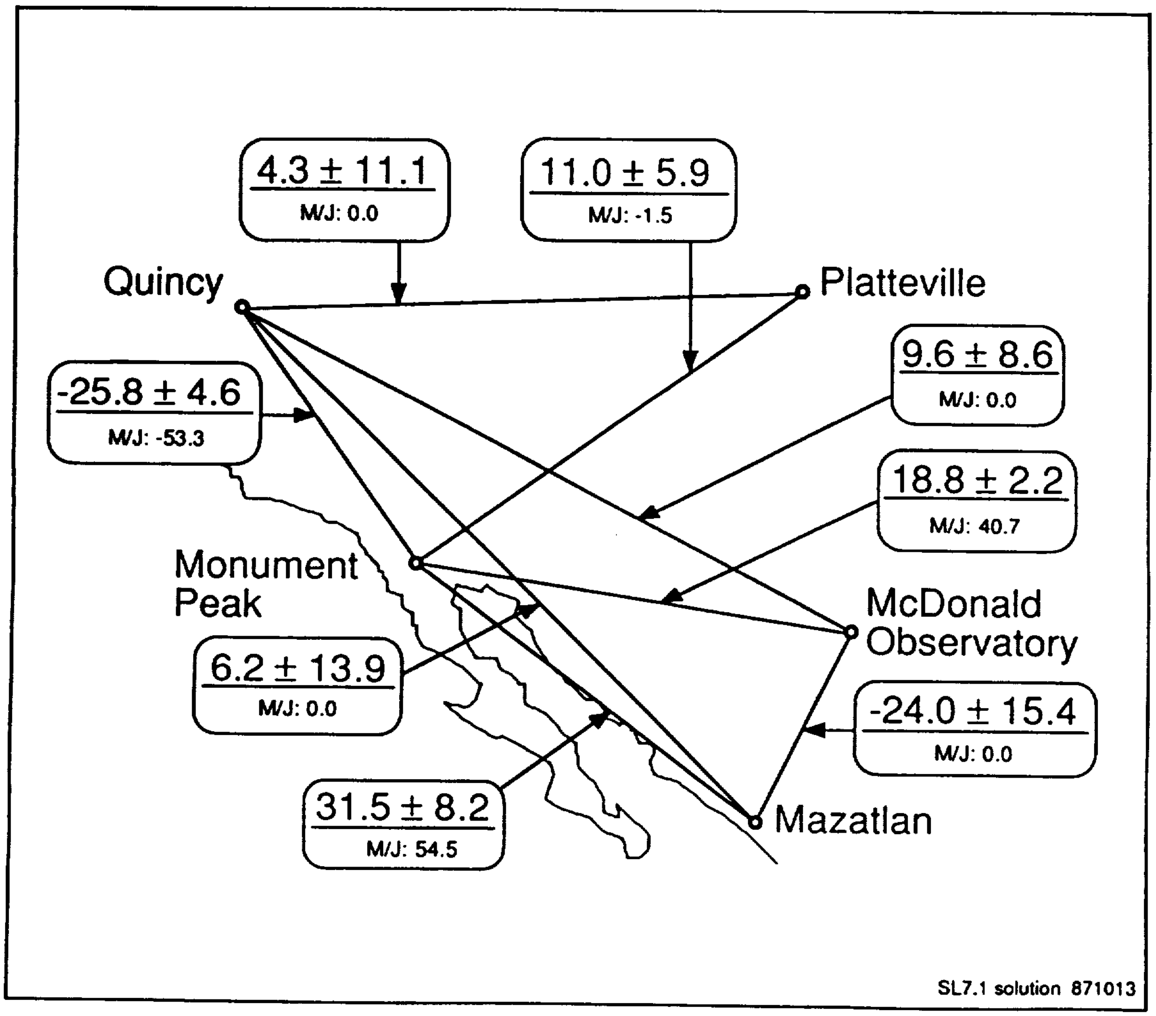


Figure II-10 Observed rates of motion for western North America (SL7.1 solution) compared with predicted values (Minster-Jordan, MJ) in mm/year.

prediction of 41 mm/yr). The observed change in the distance between Goddard and Monument Peak is 14 ± 4 mm/yr, which is consistent with the rigid plate prediction of 16 mm/yr, but since the baseline is nearly orthogonal to the sense of motion between the Pacific Plate and North American Plate in California, this observation cannot be used to address the issue of plate rigidity.

The SAFE SLR baseline is spanned by VLBI baselines from the Monument Peak, OVRO, and Quincy sites. Generally, up to seven sites participate in each VLBI observing session. The Monument Peak-OVRO baseline crosses the fault and, since OVRO is well to the east of the fault, should measure the large-scale motion of the fault. If all the motion between the Pacific and North American Plates is occurring along the fault, or in the immediately adjacent region, then no motion should be seen on the OVRO-Quincy baseline. From October 1982 to September 1986 there were four measurements of the Monument Peak-OVRO baseline, seven measurements of the OVRO-Quincy baseline, and seven measurements of the Monument Peak-Quincy baseline. Based on these data, the change is -34 ± 6mm/yr for the Monument Peak-Quincy baseline; most of this is along the Monument Peak-OVRO baseline (-25 ± 2mm/yr); and a small change occurs along the OVRO-Quincy baseline (-5 ± 3mm/yr) (see Clark et al., 1987).

Mobile VLBI measurements between 12 sites in the western U.S. have been used by Kroger et al. (1987) to infer their velocities relative to the North American Plate. To explain these results, time-dependent finite element tectonic models were developed for northern California near Point Reyes, central California between Parkfield and the Big Bend of the San Andreas, and southern California through the Salton trough region. The analysis of the VLBI data reveals significant differences in the cross-strike strain distribution between northern and southern portions of the San Andreas Fault.

Clark et al. (1987) have used the mobile VLBI data from 1982 - 1987 to derive site velocities in California and the western U.S. with respect to a reference frame defined by fixing the positions of Mojave, California, and Westford, Massachusetts. The rate and direction of motion of each station are shown in Figure II-11. The motion of the sites in southern California west of the San Andreas is closely parallel to the local trace of the fault, but none move with the full Pacific-North American RM2 rate of 56 ± 0.3 mm/yr derived by Minster and Jordan (1978). The motion increases with distance from the fault. The largest rates (80% of RM2 at Vandenberg and Fort Ord) are still significantly smaller than 56mm/yr. Kroger et al. (1987) have reported similar results. The cause of this discrepancy has been sought in offshore faults or in the Basin and Range. The group of sites in the western U.S. well to the east of the San Andreas fault show approximately similar motion to the south or southeast. If these inland sites and Fairbanks, Alaska, are used to define the reference frame, then the California base stations show a motion of 10 ± 1 mm/yr to the northwest and the Pacific coast motions are 50 ± 2 mm/yr.

Geologically-based plate motion models have also continued to evolve over the past several years. DeMets et al. (1987) have recently re-analyzed marine magnetic profiles in the Gulf of California and concluded that the spreading rate for the last 3 million years has been 48 mm/yr, which is 10 mm/yr less than previously estimated. This reduces the discrepancy between the plate motion models and observations of movement along the San Andreas Fault and Basin and Range Province to about 5 mm/yr.

The California and western U.S. measurements will be expanded and refined as more data are acquired for these sites in future years using mobile VLBI and GPS. Eventual-

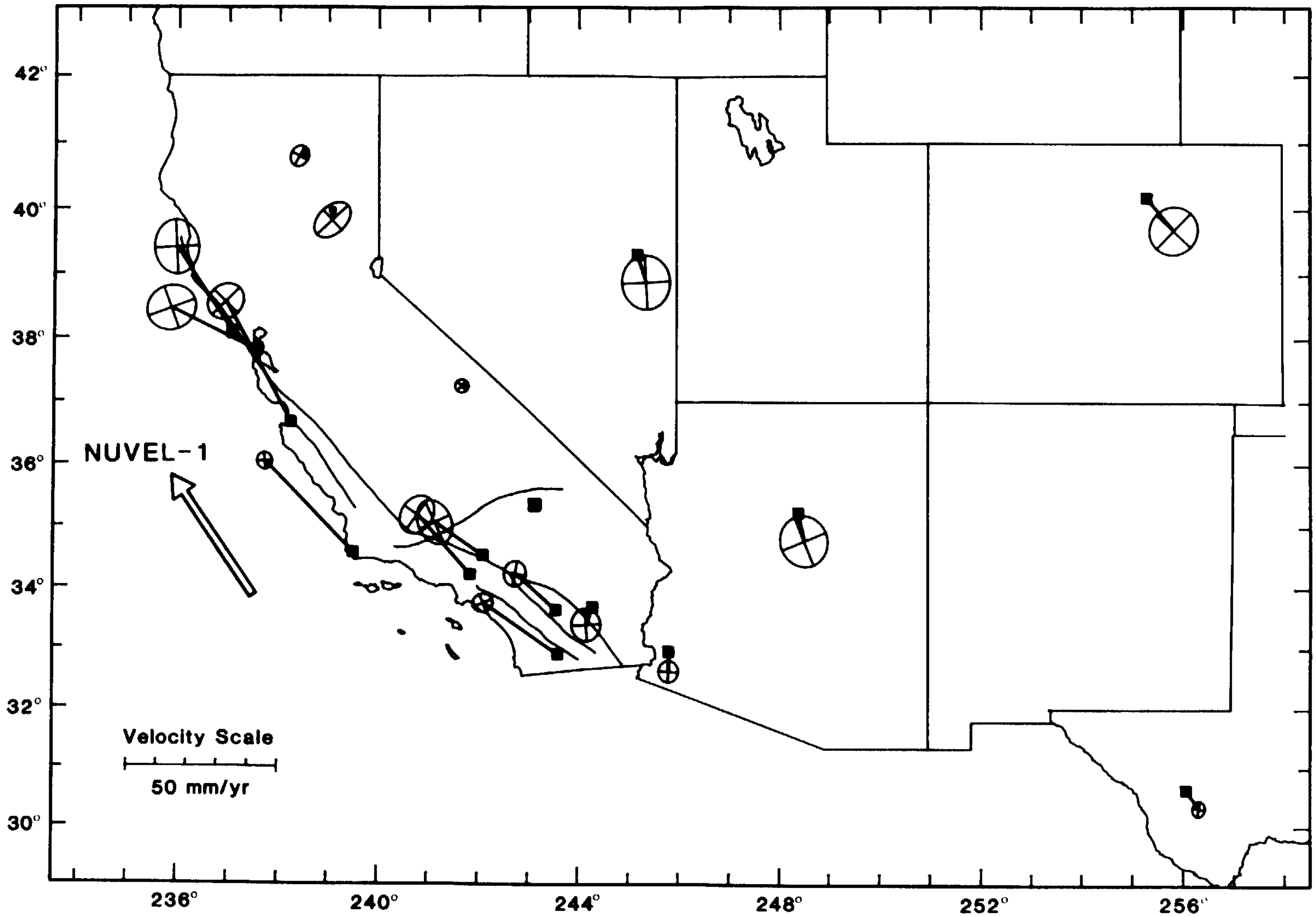


Figure II-11 Observed velocities of VLBI sites in California and the western U.S.: 1982-1987.

ly, it should be possible to produce a strain field map for most of California and to begin monitoring strain field changes. This, in turn, should prove to be of great significance in understanding crustal hazards in the western U.S.

The mobile VLBI observations in Alaska acquired during 1984-1986 GAPE campaigns indicate different tectonic behavior at the various sites (Figure II-12). In the reference frame defined by Fairbanks, Alaska, and the sites well east of the San Andreas in California, Sand Point shows no significant motion (but the data are weak); Kodiak shows 18 ± 7 mm/year to the west, while Cape Yakataga shows 37 ± 7 mm/year at an azimuth of 342°. There is no significant motion at Nome or Sourdough. Some of the strain in the seismic gap at Cape Yakataga is evidently being absorbed by creep.

B. EARTH ORIENTATION STUDIES

Monitoring of changes in Earth orientation with time using SLR, LLR, and VLBI networks is necessary to achieve the primary goals of the CDP, namely, the detection of tectonic displacements and present rates of plate motions. Moreover, the orientation history has intrinsic scientific value and provides unique information related to Earth's internal structure, atmospheric angular momentum and air pressure field, solid and ocean tides, core-mantle coupling mechanisms and large scale climatic processes.

Earth orientation changes can be classified into three major categories: (1) deviations from uniform rotation about the Earth's spin axis, where the accumulated angle is UT1; (2) motion of the pole of the Earth's spin axis over its surface; and (3) uniform precession and periodic nutations of the spin axis relative to inertial space. Each motion is also affected by the Earth's dynamic gravity field which, if observed by Lageos, enables the isolation of a subset of the excitation mechanisms affecting Earth orientation. The accomplishments achieved with nearly a decade of Lageos-I data, seven years of POLARIS/IRIS VLBI data, and nearly two decades of LLR, have been remarkable. The major achievements in improved accuracy and scientific interpretation for each of these data types and observing systems are discussed below.

1. Earth Rotation: UT1

The largest changes in Earth orientation (except for precession) occur in Earth rotation. Crude records of UT1 going back to the 1650's have been constructed from astrometric data in which the motion of planets and moon serve as accurate clocks. The use of quartz clocks in the 1930's allowed detection of seasonal variations in UT1. The adoption of atomic clocks in 1955 eliminated clock errors as a serious error source, leaving positional uncertainty as the major error source. Until 1988, the Bureau International de l'Heure (BIH) regularly collected data from approximately 50 to 80 astrometric observatories scattered over the world, which determined the time of the meridian passage of stars. The uncertainty of these measurements are no better than a few milliseconds, and these data are plagued by systematic error sources. The new techniques have reduced measurement uncertainty to 0.2 ms or better and require fewer observatories and shorter averaging times, so that changes which occur over a few weeks can now be routinely detected. (In 1988 a new service, the International Earth Rotation Service, replaced BIH; the IERS bulletins contain VLBI, SLR, and LLR results which were reported from observatories all over the world.)

Initial research in this area naturally focused on comparison studies of SLR, LLR,

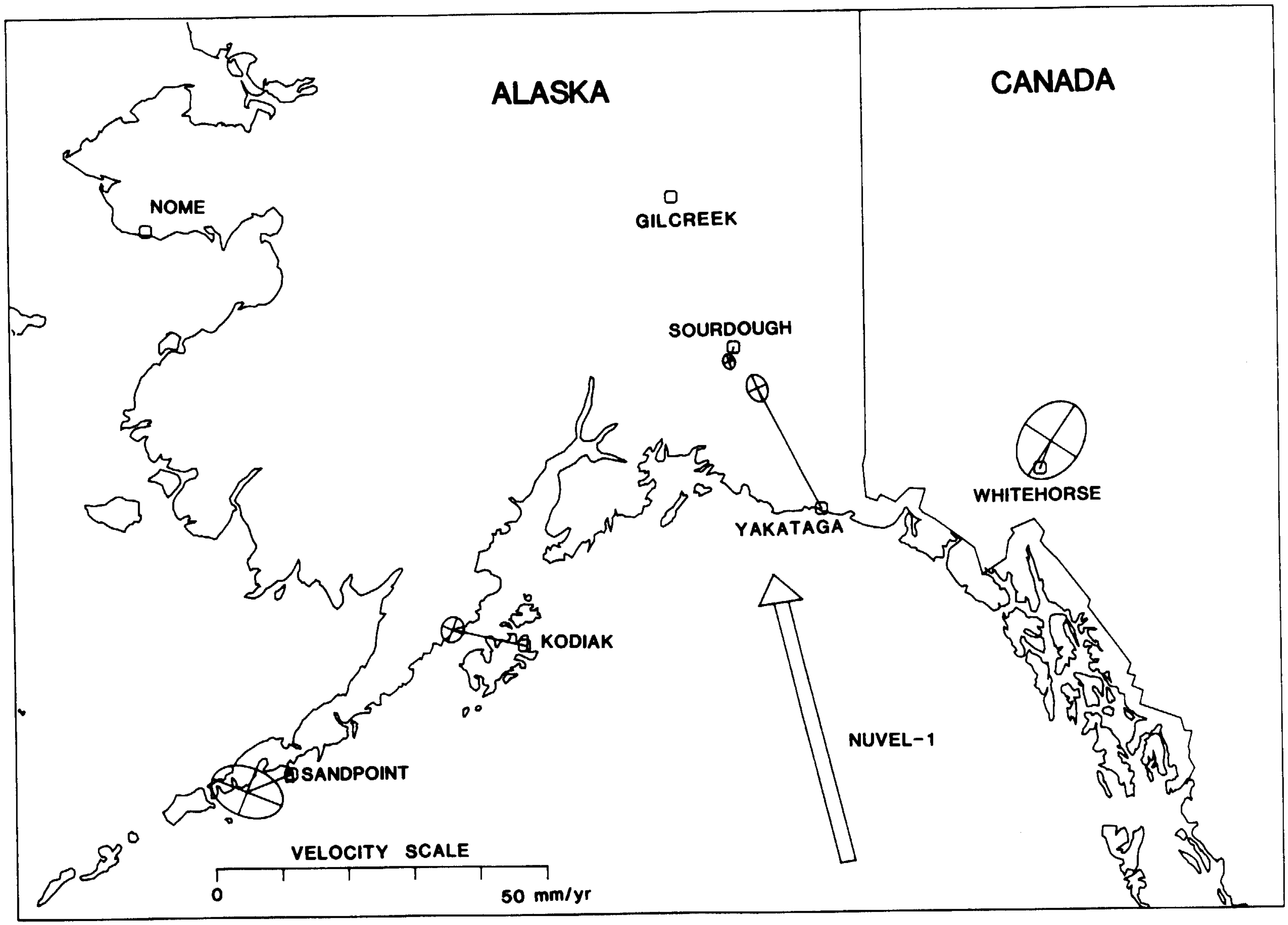


Figure II-12 Observed velocities of VLBI sites in Alaska and Canada: 1984-1986.

VLBI and BIH astrometric data sets (e.g., Robertson et al., 1983; Dickey et al., 1984). Several different data filters such as Gaussian, Fourier, Vondrak, Wiener and Kalman smoothing (Morabito et al., 1986; Dickey et al., 1985; Feissel and Lawandowski, 1984) have been examined to determine which might give the best possible, uniformly valid UT1 and polar motion histories. Combination solutions have also been constructed which attempt to incorporate the strengths of each data type (e.g., King et al., 1984; Dickey and Eubanks, 1985).

Fortunately, the improvements in UT1 have been matched by development of improved models of Earth's global atmospheric angular momentum (AAM). In these models, surface wind data and other meteorological measurements are input into large computer models used for weather forecasting. Estimates of the AAM are currently available based on the reduction and analysis of meteorological data for weather forecasting at four Centers: the European Centre for Medium-Range Weather Forecasts (ECMWF), the Japanese Meteorological Agency (JMA), the U.S. National Meteorological Center (NMC), and the United Kingdom Meteorological Office. A variety of atmospheric variables, including the local wind velocity vector, are estimated at each model grid point. The total angular momentum is estimated at twelve-hour or twenty-four hour intervals (depending on the Service used) from the appropriate integral of the grid point wind velocity and surface pressure estimates from the current update. Calculations of AAM are generally computed using the formulation of Barnes et al. (1983); their effective atmospheric AAM function, X, a three-dimensional vector, includes Love number corrections for rotational and surface loading deformation of the Earth and can be evaluated directly from meteorological data.

Except for isolated offsets, AAM models agree at about the 10% level (Eubanks et al., 1983). There should be a balance between AAM and angular momentum changes inferred from UT1 data in the absence of other exciting mechanisms. Until recently, there were significant discrepancies at annual and semi-annual periods (Eubanks et al., 1985a), but these are apparently removed once the stratospheric wind (1 to 100 millibars) contribution to AAM is included (Rosen and Salstein, 1985). Figure II-13 shows a comparison of the time series of daily values of the angular momentum of the entire atmosphere based on tropospheric data from NMC and stratospheric data for 1980-1981 from Hirota et al. (1983) and the three-day means of observed changes in the LOD. The mean value of each series during 1980-1981 has been removed, as have solid-body tidal terms from changes in LOD. Seasonal contributions to LOD from other sources such as the Antarctic circumpolar ocean current and ground water changes are smaller than the differences between models. However, ground water changes (Wilson et al., 1987) and snow cover variations (Chao, 1987) primarily affect UT1 by changing the polar moment of inertia. These seasonal changes also affect the external gravity field and so can be observed by Lageos.

Several comparative studies have contributed to understanding of global atmospheric processes such as the location of major wind changes, detection of the 40 to 60 day oscillations (Feisel and Gambis, 1980; Langley et al., 1981) and the recent El Nino phenomena (Rosen et al., 1984; Chao, 1984; Eubanks et al., 1985a). In Figure II-14(a), axial angular momentum is shown in each of 22 equal-area belts over the globe on a daily basis for the winter of 1982-83: contours are plotted every 5×10^{24} kg M^2S^{-1}; negative values correspond to easterly momentum and are dashed. Figure II-14(b) illustrates the difference between the belt angular momentum values given in Figure II-14(a) and the average of the belt angular momentum values for the four winters beginning in December 1976. Positive values indicate a larger value existed during the

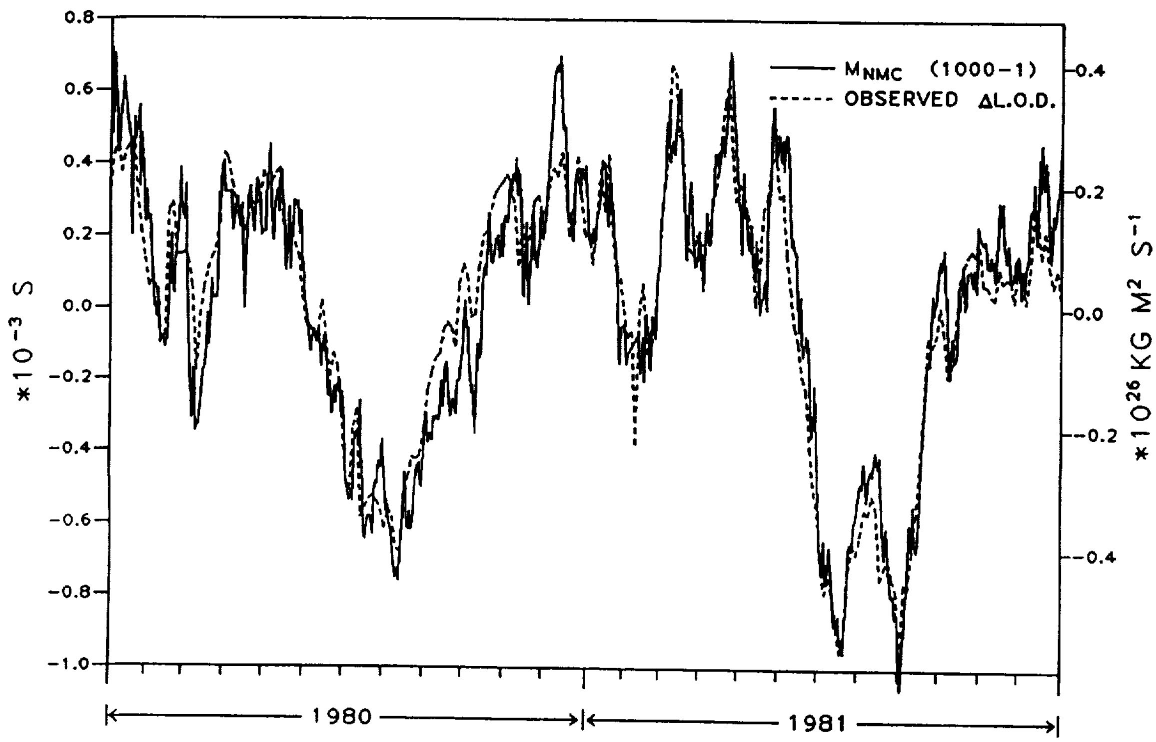


Figure II-13 Comparison of the time series of daily values of the angular momentum of the entire atmosphere based on tropospheric data from the National Meteorological center (NMC) and stratospheric data for 1980-1981 with the three-day means of observed changes in the LOD.

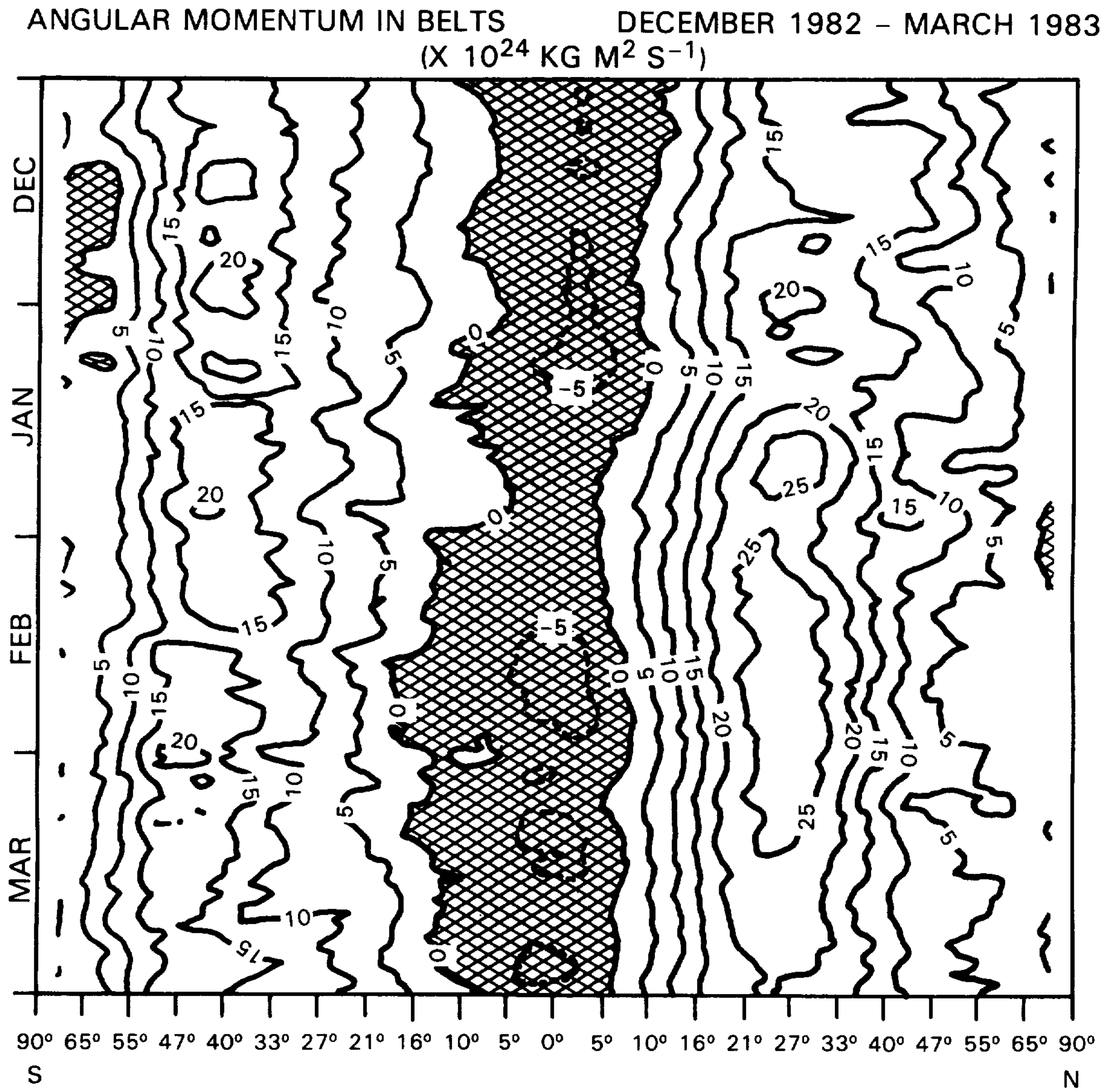


Figure II-14(a) Axial angular momentum in each of 22 equal-area belts over the globe on a daily basis for the winter of 1982-83: contours are plotted every 5 x 10^{24} kg M^2S^{-1}; negative values correspond to easterly momentum and are dashed.

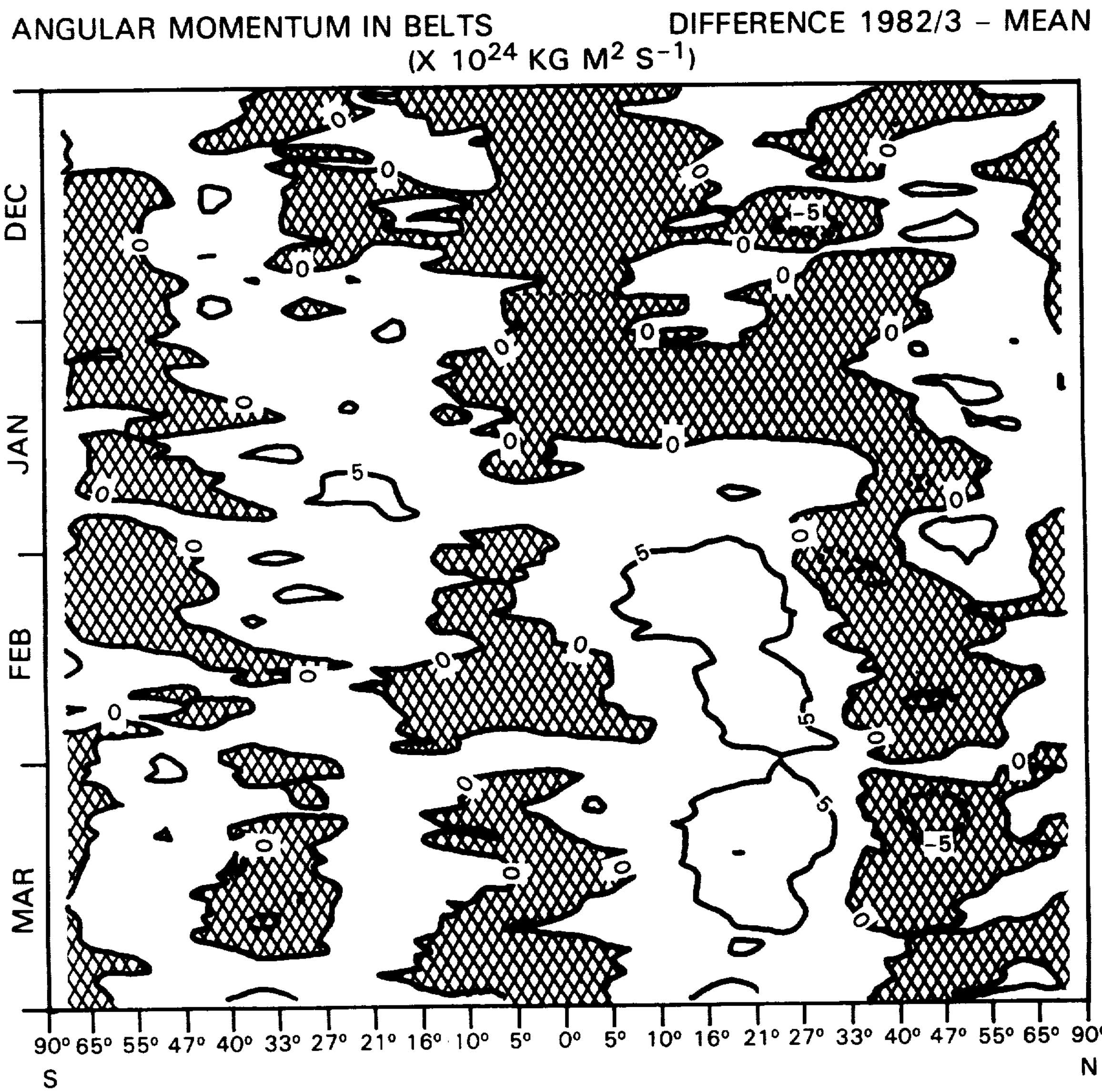


Figure II-14(b) Difference between the belt angular momentum values given in Figure II-14(a) and the average of the belt angular momentum values for the four winters beginning in December 1976.

El Nino winter than in the longer-term mean; negative values are shaded. In Figure II-15, from Chao, the excess LOD is compared with values for the Southern Oscillation Index (SOI) for the period of 1957-1983. The arrows in the figure indicate the occurrence of El Nino events, the length of the arrow is proportional to the severity of the El Nino. It appears that LOD variations for spectral periods of the order of one year or less can be used as a proxy index of global wind fluctuations (Salstein and Rosen, 1985).

The AAM data are sufficiently accurate so that its removal from the UT1 record can be used to examine the role of slow processes such as changes in the fluid core angular momentum. Even without AAM, the magnitude of the long-term LOD changes rule out contributions from the atmosphere. The construction of fluid core angular momentum variations using models of core-mantle hydromagnetic coupling and surface magnetic field data has just been initiated. Recently, preliminary maps of the geostrophic fluid velocity at the core surface have been constructed from magnetic field maps covering several years (Voorhies and Backus, 1985; LeMouel et al., 1985). At roughly the same time, maps of large-scale core topography have been obtained from a combination of mantle flow models and seismic tomography (Hager et al., 1985). Torques on the mantle caused by the lateral pressure exerted on the core-mantle boundary (CMB) topography can be calculated using a mountain torque model. A method for the calculation of torque using the geomagnetic data and the results of seismic tomography has been outlined by Hide (1986). The initial calculations of LOD changes (Hager et al., 1985) using a preliminary CMB topography model agrees in sign with the observed decade-scale LOD changes, but are too large by a factor of five to ten. Hager finds that the CMB topography and LOD changes can be reduced by introducing a chemically distinct D" layer just above the CMB in which the major topography variations are at the top of the D" layer. Since the density contrast at the top of D" is small compared to that at the CMB, the topography necessary to account for the gravity and seismic residuals must be correspondingly larger, perhaps as much as 50 Km. Numerical convection studies of a thermal boundary layer with temperature-sensitive viscosity show that small-scale thermal plumes might also develop at the base of the mantle, and thus, small-scale topography in the boundary layer can also be expected. Unfortunately, the CMB torque calculations cannot be used to accurately assess the CMB topography. Precise calculations of the torques exerted at the CMB will require new, more global magnetic field measurements from a platform similar to the proposed Magnetic Field Explorer (MFE) Mission.

Comparison of Lageos-I orbit nodal residuals with accurate UT1 from other techniques can be used to isolate changes in rotation (UT1) caused by mass redistribution which effects Earth's oblateness or the J_2 gravity coefficient. Figure II-16 shows the nodel residual once signatures caused by short-period tidal constituents are removed: in (a) the diurnal, semi-diurnal and a nominal zonal tidal model is removed; in (b) a long-period signature (due to t_2 and 18.6 year period terms) is removed; and in (c) seasonal terms (annual and semi-annual) are removed. The residuals contain an obvious annual term, thought to be caused by a combination of ground water and air pressure changes and are equivalent to a 2 ms amplitude UT1 signature. The long-period signature is believed to be due to ongoing post-glacial rebound, although contributions from a non-equilibrium 18.6 year zonal tide and present-day glacial melting may be important. The long-period change is equivalent to a rate of change of J_2 of between -2 and -3 x 10^{-11} per year (Yoder et al., 1983; Rubincam, 1984), and implies that the average mantle viscosity is about 3 x 10^{22} poise.

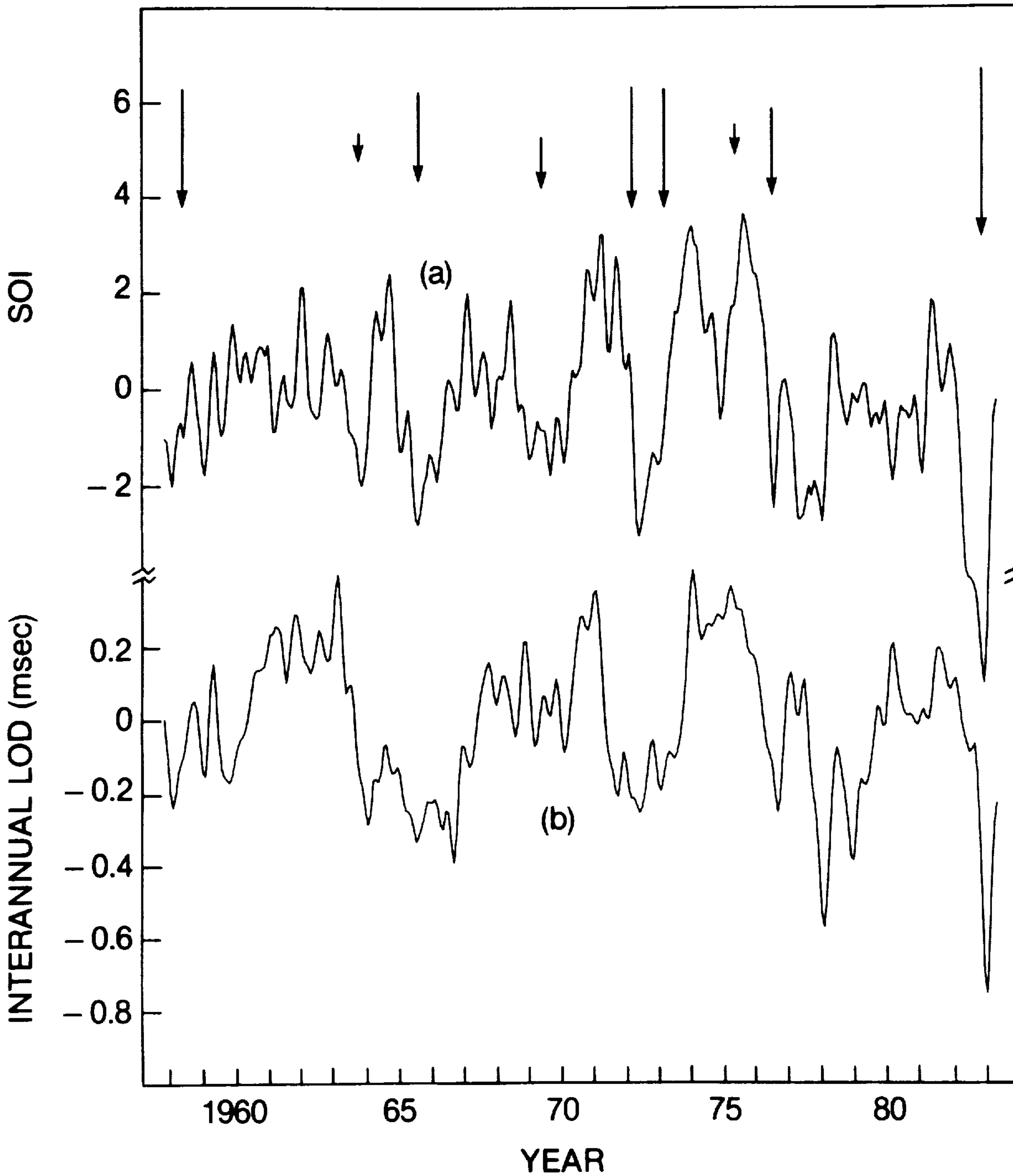


Figure II-15 Excess LOD compared with values for the Southern Oscillation Index (SOI) for the period of 1957-1983. The arrows in the figure indicate the occurrence of El Nino events, the length of the arrow is proportional to the severity of the El Nino.

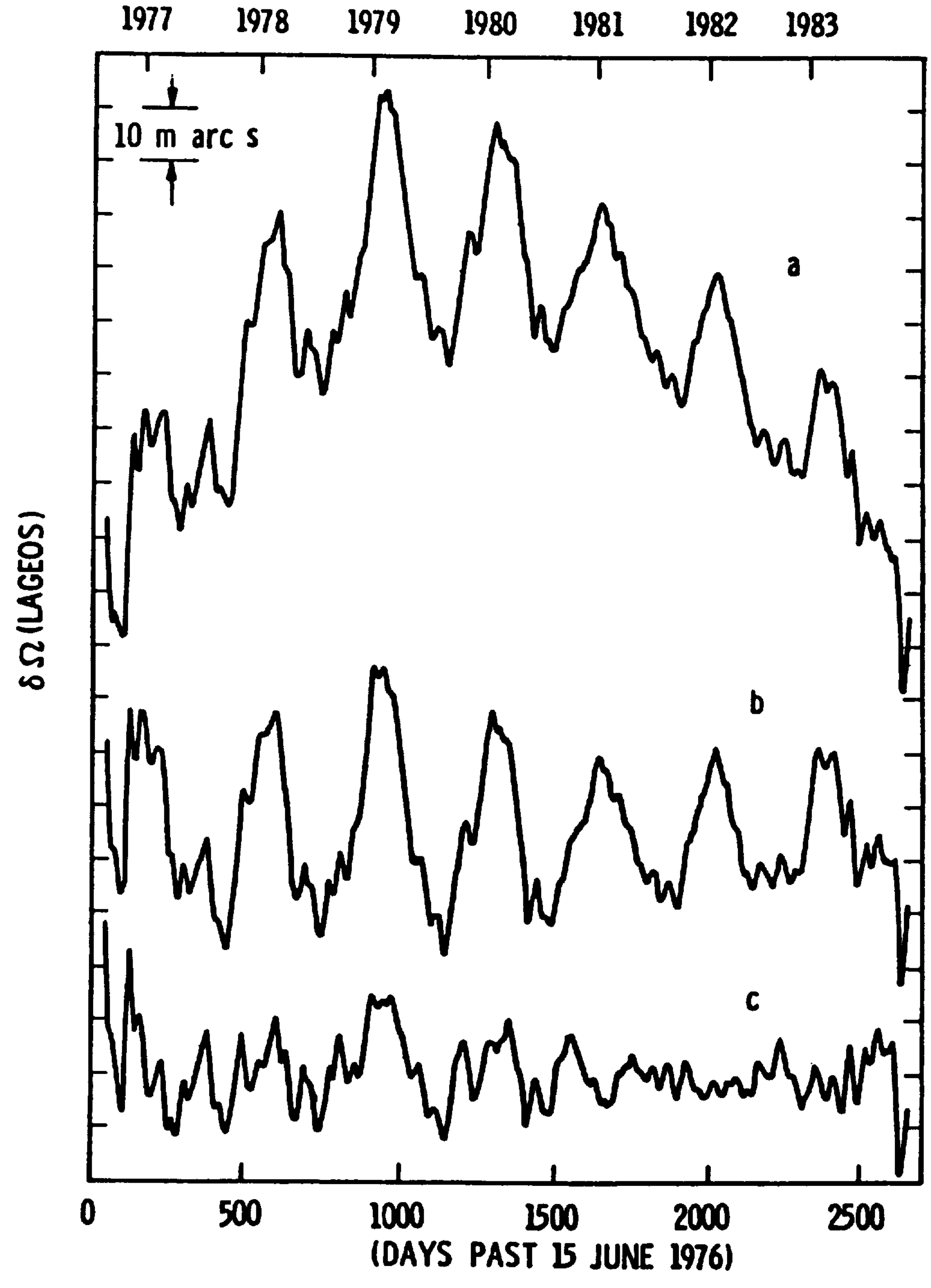


Figure II-16 Nodel residual of the Lageos-1 orbit once signatures caused by short-period tidal constituents are removed: in (a) the diurnal, semi-diurnal and a nominal zonal tidal model is removed; in (b) a long-period signature (due to t_2 and 18.6 year period terms) is removed; and in (c) seasonal terms (annual and semi-annual) are removed.

2. Polar Motion

The small, periodic, and secular drift of the spin axis with respect to Earth's symmetry axis has been regularly observed by five or more astronomic observatories for over 80 years. The dominant signatures in these data include a forced annual oscillation with mean amplitude of about 100 mas, and a free Eulerian oscillation or "Chandler Wobble" with variable amplitude (less than 300 mas). The remaining signatures include a 3 mas/year drift of the spin pole toward North America that is generally accepted as real, while the existence of the approximately 20 to 30 year "Markowitz Wobble" is more controversial (Ming and Danan, 1987).

The focus of research on this phenomenon has concentrated on a study of mechanisms which excite and damp the Chandler Wobble. Global changes in surface air pressure largely account for the annual oscillation. However, it is less certain that non-seasonal air pressure variations can account for the observed Chandler Wobble. Recent comparisons (Barnes et al., 1983; Hide, 1985) of the last five years of accurate polar motion data with the predicted pole position from air pressure data (see Figure II-17) tend to support this as the dominant excitation mechanism, contrary to the conclusion of Wahr (1983) from analysis of about 80 years of the less accurate ILS astrometric data. The contribution of ground water to the Chandler Wobble excitation has yet to be calculated. The excitation of both polar motion and LOD due to earthquakes has been calculated by Gross (1987) who finds that the predicted LOD changes from 1977 to 1985 are of the order of 0.1 ms, well below observations. Similar results are obtained for polar motion. Although earthquakes have not been a significant source of excitation during the present epoch, very large events such as the 1960 Chilean and the 1964 Alaskan earthquakes were predicted to produce 23 mas and 7 mas changes in polar motion, respectively. The effects of similar events in the future promise a measurable signal which should provide an independent test of seismic moment-magnitude relations.

Another curiosity linking atmospheric pressure and polar motion is the correlation between the Southern Oscillation Index (SOI) and ILS polar motion (Chao, 1984). This index measures the air pressure difference across the Pacific, and is thus correlated with the El Nino phenomena.

Recently, short-period polar motions with spectral peaks near ten days have been detected and correlated with air pressure derived excitation functions (Eubanks et al., 1987). The ten-day pressure wave is a westward propagating, retrograde barotropic mode with approximately 1/2 mbar amplitude. The Kalman-smoothed cross-correlation function of the derived- and predicted excitation functions X_1 and X_2 are shown in Figure II-18. The maximum correlation occurs at zero lag and is 0.41 for X_1 and 0.55 for X_2. Although modest, the correlation is statistically significant.

Modern space techniques have resulted in a ten-fold reduction in the uncertainty of pole determination at five-day intervals. Solutions for pole position from SLR and VLBI now agree at about the 5 cm or 2 mas level (see Figure II-19). Continual monitoring of polar motion combined with improved models of air pressure and ground water may resolve the degree to which meteorology drives polar motion. The observed secular polar motion is believed to be caused by post-glacial rebound (Peltier, 1984; Sabadini et al., 1984), with smaller contributions from present-day melting of glaciers and plate motion. The observed pole drift depends in part on the tectonic motions of station sites constituting the observing network (see Figure II-20(a) and (b) from Tapley et al.,

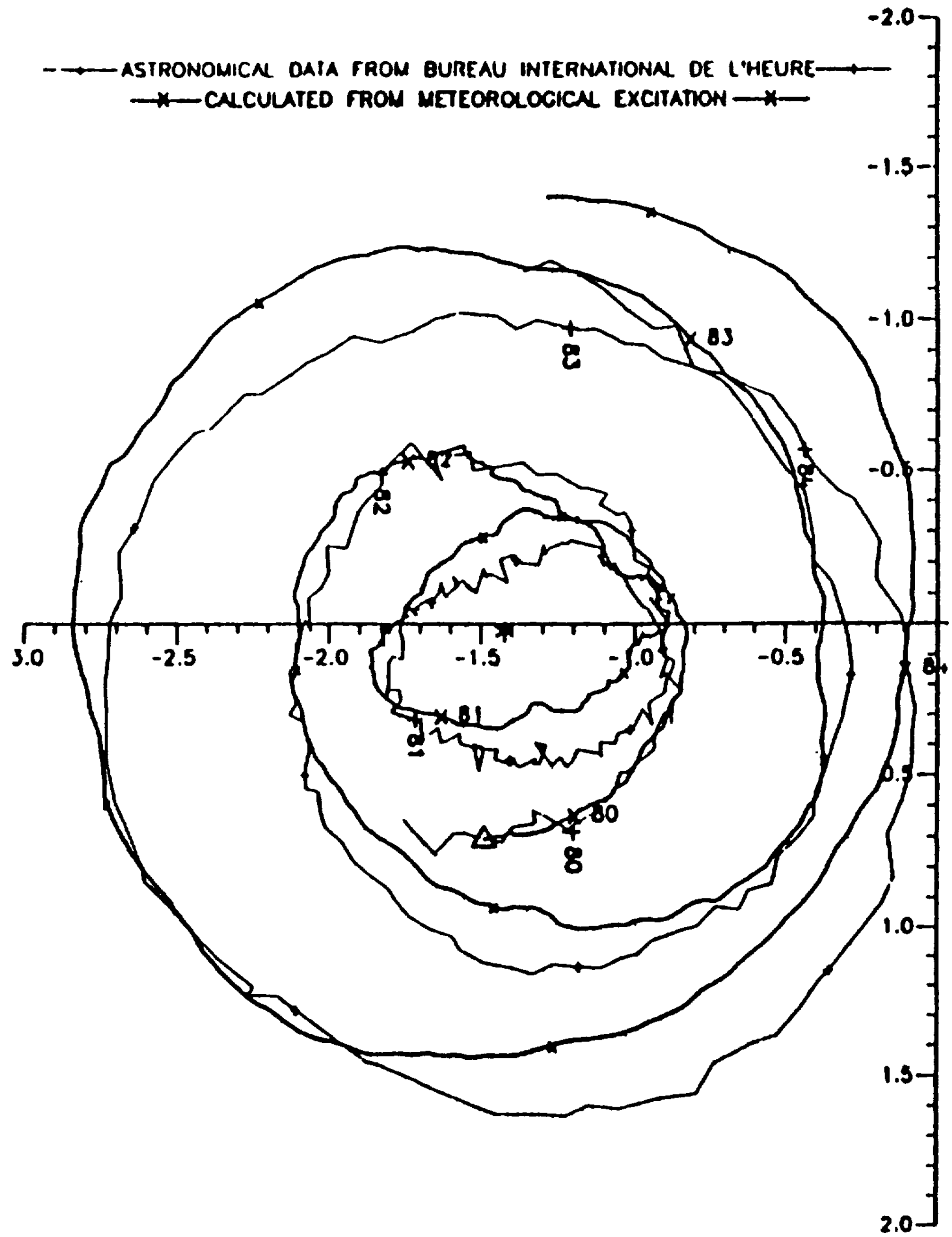


Figure II-17 Comparison of the last five years of accurate polar motion data with the predicted pole position from air pressure data.

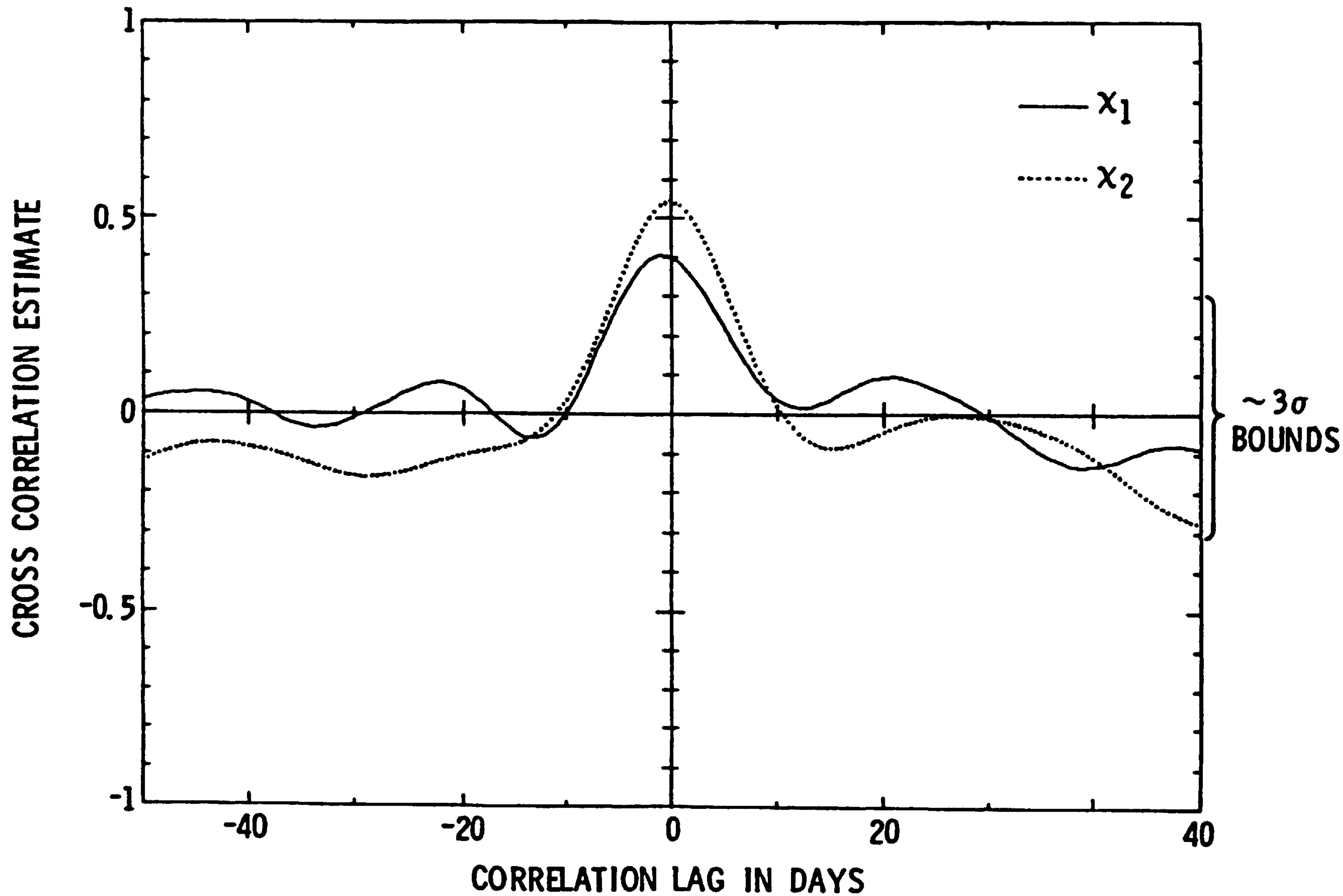


Figure II-18 Kalman-smoothed cross-correlation function of the derived- and predicted excitation functions X_1 and X_2.

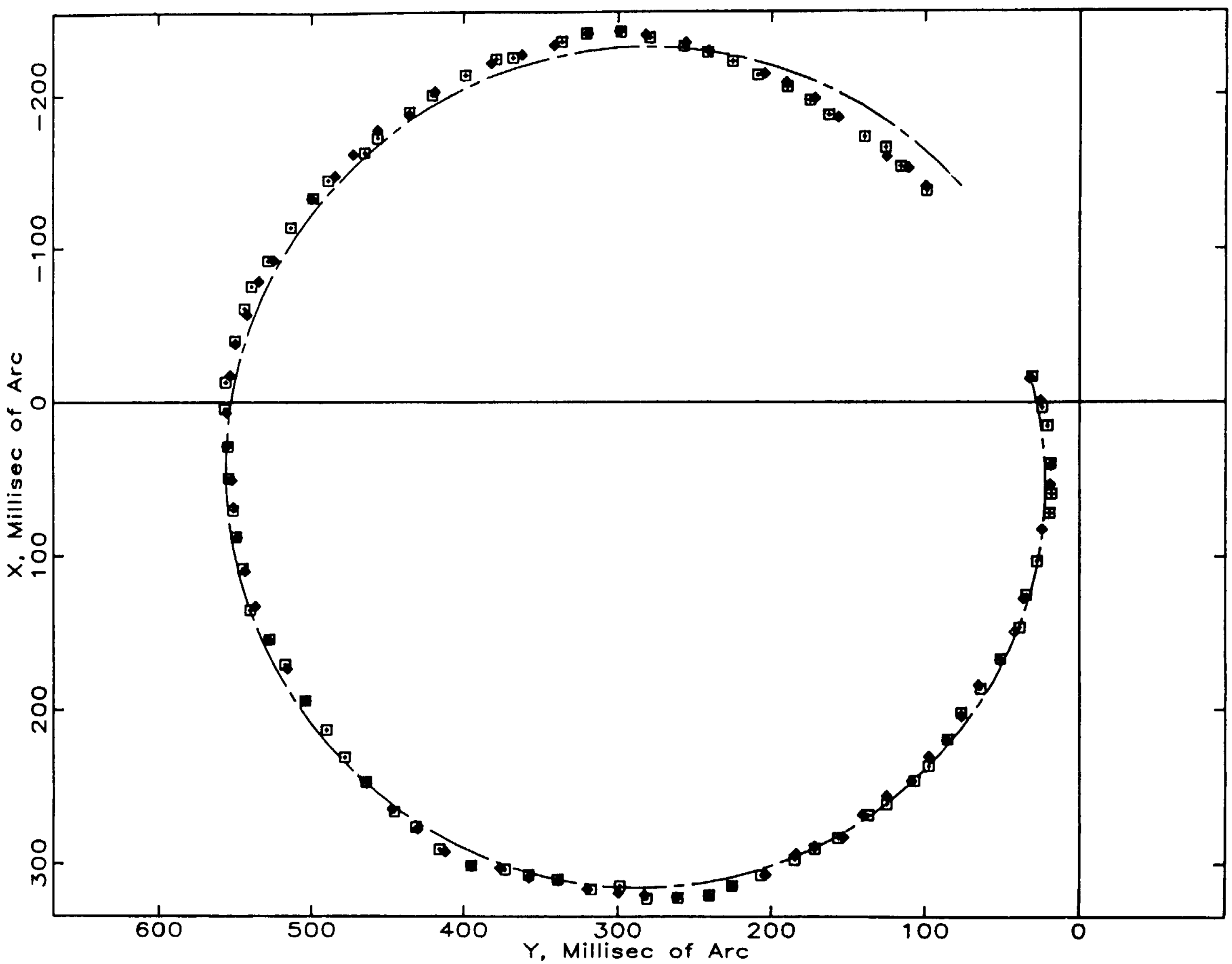


Figure II-19 Comparison of SLR- and VLBI-determined positions for the pole.

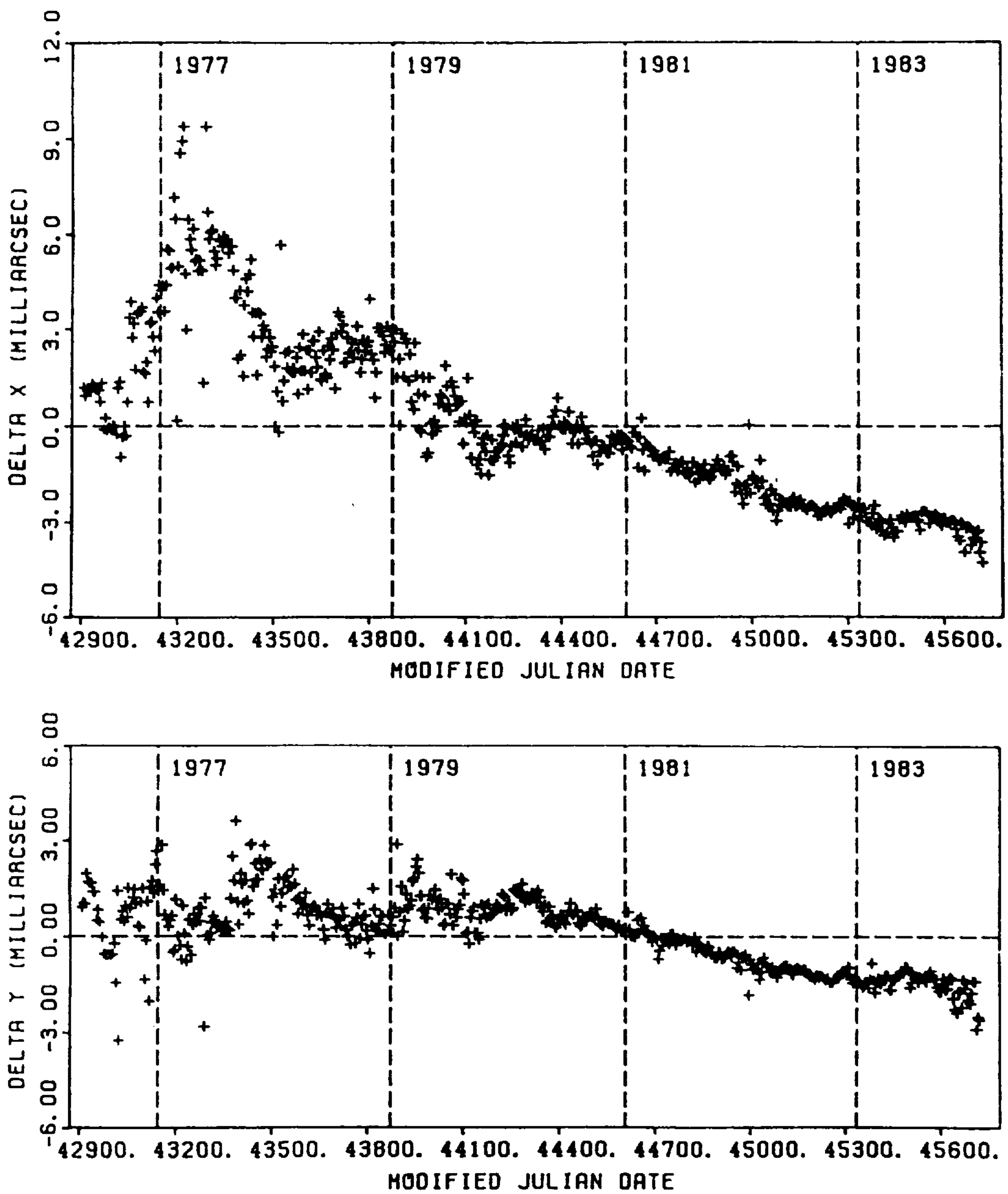


Figure II-20 Differences in Lageos-derived Earth rotation parameters due to modeling plate motions with Minster-Jordan AM-2 model.

1985a), which can be largely removed by application of a tectonic plate model.

3. Precession and Nutation

The Sun and Moon exert gravitational torques on the Earth's figure, causing its spin axis to precess and also execute several small periodic nutations. The largest nutation is about 10 arcseconds in amplitude, and is driven by the 18.6 year precession of the moon's orbit. Nutations with annual, semi-annual and fortnightly periods are also significant. Free nutation of the fluid core and solid inner core of the Earth are also possible, but require an excitation mechanism.

Wahr (1981) constructed a modern nutation theory which takes into consideration the effects of the Earth's elastic and density structure as well as atmospheric and ocean tides (Sasao and Wahr, 1981) on these amplitudes. A solution for the precession constant (correction = 0.10 ± 0.30 arcseconds per century) and several of the largest nutation terms have been obtained using LLR data with results in agreement with conventional astrometric studies (Newhall et al., 1987). Results from various VLBI programs, POLARIS/IRIS (Carter et al., 1984), CDP (Ryan and Ma, 1987), and the JPL Deep Space Program (Sovers et al., 1984), has allowed examination of corrections to the shorter-period terms.

The most recent residual nutation results (Herring et al., 1987), shown in Figure II-21 were obtained during 370 observing sessions carried out between July 1980 and December 1986. These results show the deviation of the spin axis from that predicted by Wahr's theory in terms of the residual obliquity and projected longitude. An annual signature is clearly visible in the data: retrograde correction = 2.06 ± 0.10 increase in the in-phase component and a 0.33 ± 0.10 mas 90^0 out-of-phase component. Independent analysis of POLARIS data (Himwich and Harder, 1987) and combined POLARIS/IRIS and Deep Space Network (DSN) VLBI data confirm this result (Eubanks et al., 1985b). Significant semi-annual and long-period drifts are also present. Herring et al. (1987) also obtained a marginal solution of the fluid core free nutation (FCN amplitude = 0.33 ± 0.10 mas) consistent with an altered FCN period of 434 days. (An analysis of the relative gravimetric bands for the K_1, P_1, and O_1 tides using a superconducting gravimeter confirms this interpretation (Richter and Zurn, 1987)). Instead of claiming a detection, Herring et al. (1987) state that the upper bound of the FCN amplitude is 0.6 mas. Perhaps part of the reticence in claiming a detection is due to the possibility that the rigid body nutation theory of Kihoshita (1977) is deficient. Kubo and Fukashima (1987) have developed a method for numerically integrating Euler's rigid body equations in which the wobble mode is suppressed. They obtain large corrections to the nominal theory for the 9.3 and 18.6 year nutations of order 0.5 mas. Spectral analysis of the residuals reveal power near 430 days with an amplitude of approximately 0.03 mas. The FCN resonance could boost this by a factor of ten.

The effects of solid friction, frequency dispersion of the elastic structure, and ocean tides on the nutations have also been estimated (Wahr and Sasao, 1981), and change some nutation amplitudes by as much as 0.5 mas. None of these mechanisms appear to account for the large annual correction.

Gwinn et al. (1986) argue that the annual signature and changed FCN period can be understood if the nominal ellipticity of the core-mantle boundary is increased by about 5%. This change in the ellipticity is equivalent to an increase in the mean equatorial axis relative to the polar axis of 0.5 km, and must be the result of mantle convection.

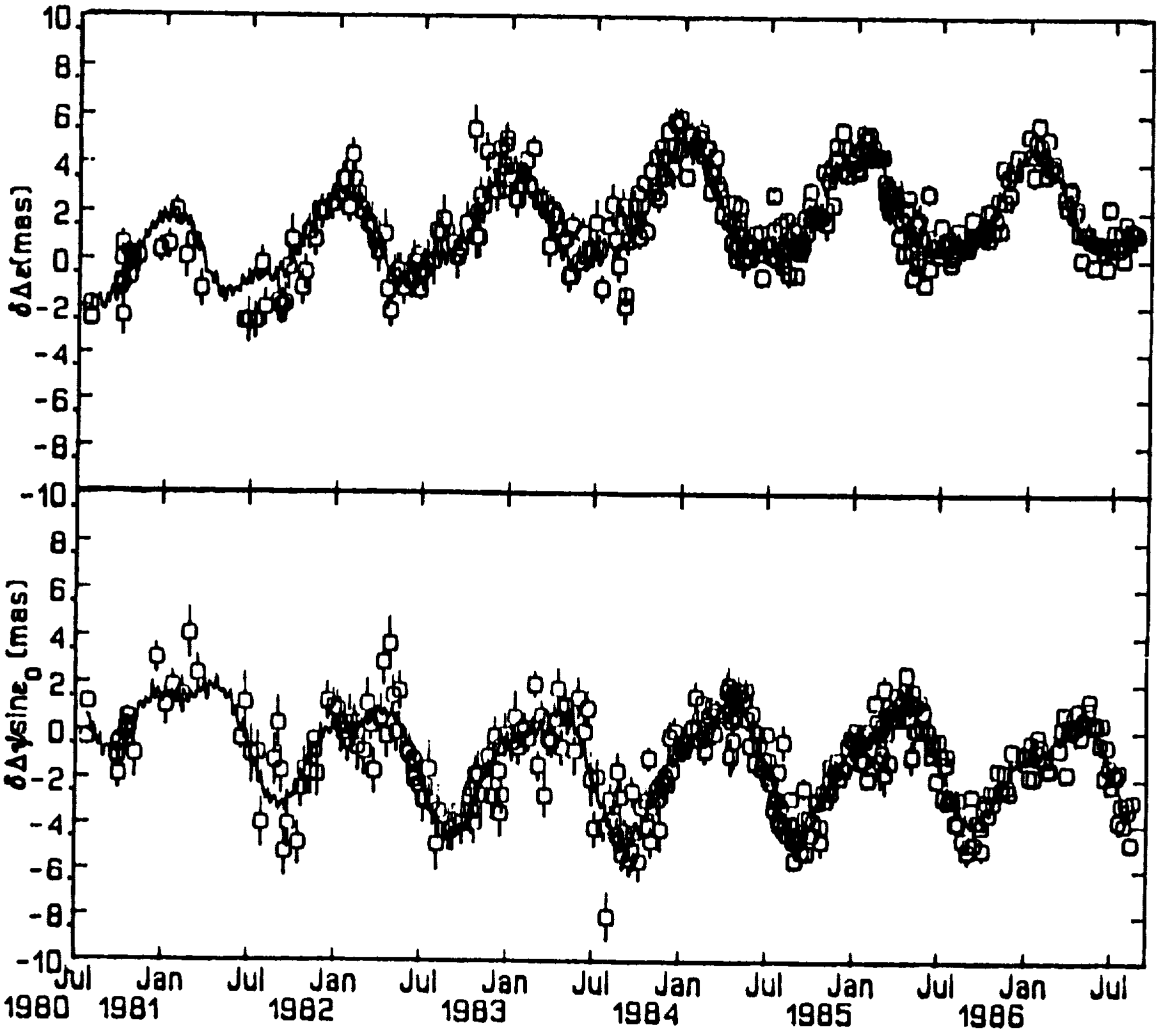


Figure II-21 Deviation of the spin axis from that predicted by Wahr's theory in terms of the residual obliquity and projected longitude.

Estimates of the core shape have recently been obtained from seismic tomography (Hager et al., 1985), which indicate an increase of about 15% in core ellipticity. However, the introduction of a D" layer at the base of the mantle can substantially reduce CMB topography where the size of the reduction depends on the layer's thickness and viscosity.

4. Project MERIT

The new space geodetic measurements have created the potential for further profound advances. This has led to a number of national and international programs to promote the collection and analysis of data from all techniques. MERIT (Monitor Earth Rotation and Intercompare the Techniques of Observation and Analysis), an international effort to evaluate geodetic techniques is sponsored by the International Union of Geodesy and Geophysics (IUGG) and the International Astronomical Union (IAU) (Wilkins, 1980). During its main campaign (September 1983 - October 1984), MERIT yielded the most accurate Earth rotation data ever obtained. This effort was extended until the beginning of the new International Earth Rotation Service (IERS) in January 1988. Daily (Eanes et al., 1984) and even sub-daily (Robertson et al., 1985) values of UT1 with accuracies well below the millisecond level have been reported during the intensive part of the MERIT campaign (April - June 1984). Daily polar motion determinations were also obtained during this period (Eanes et al., 1984; Tapley et al., 1985b). These results were reported at the Third MERIT Workshop held in conjunction with the International Conference on Earth Rotation and the Terrestrial Reference Frame (Mueller, 1985).

Analysis and interpretation of the new data sets generated by routine VLBI, SLR, and LLR observing programs have been either the main topic or figured prominently in several subsequent meetings. These include IAU Symposium No. 128: Earth Rotation and Reference Frames for Geodesy and Geodynamics (Babcock and Wilkins, 1987), and the 1987 IUGG Symposium on Earth Rotation held in Vancouver, Canada.

C. GEOPOTENTIAL RESEARCH

1. Gravity Field

Knowledge of the Earth's gravity field is fundamental to understanding the dynamics of the Earth. Data on the spatial and temporal variations of the field provides information on the Earth's physical properties and geodynamic processes and places constraints on models of the internal structure of the Earth. In oceanography, an understanding of the departure of the actual sea surface from a unique equipotential surface of the Earth's gravity field (the geoid) can reveal information on ocean circulation. Other areas which benefit from knowledge of the Earth's gravity field are satellite orbit determination and classical geodesy, yielding, in particular, plate motion estimations from the Lageos orbits.

A comparison of the "quality" of gravity field models developed during the past 17 years is provided in Figure II-22. By 1979, gravity field models had been developed extensively by groups at the Smithsonian Astrophysical Observatory (SAO) and the Goddard Space Flight Center and modeling was well underway in Europe. These models were based on reasonably good measurements and orbit perturbation data for a large

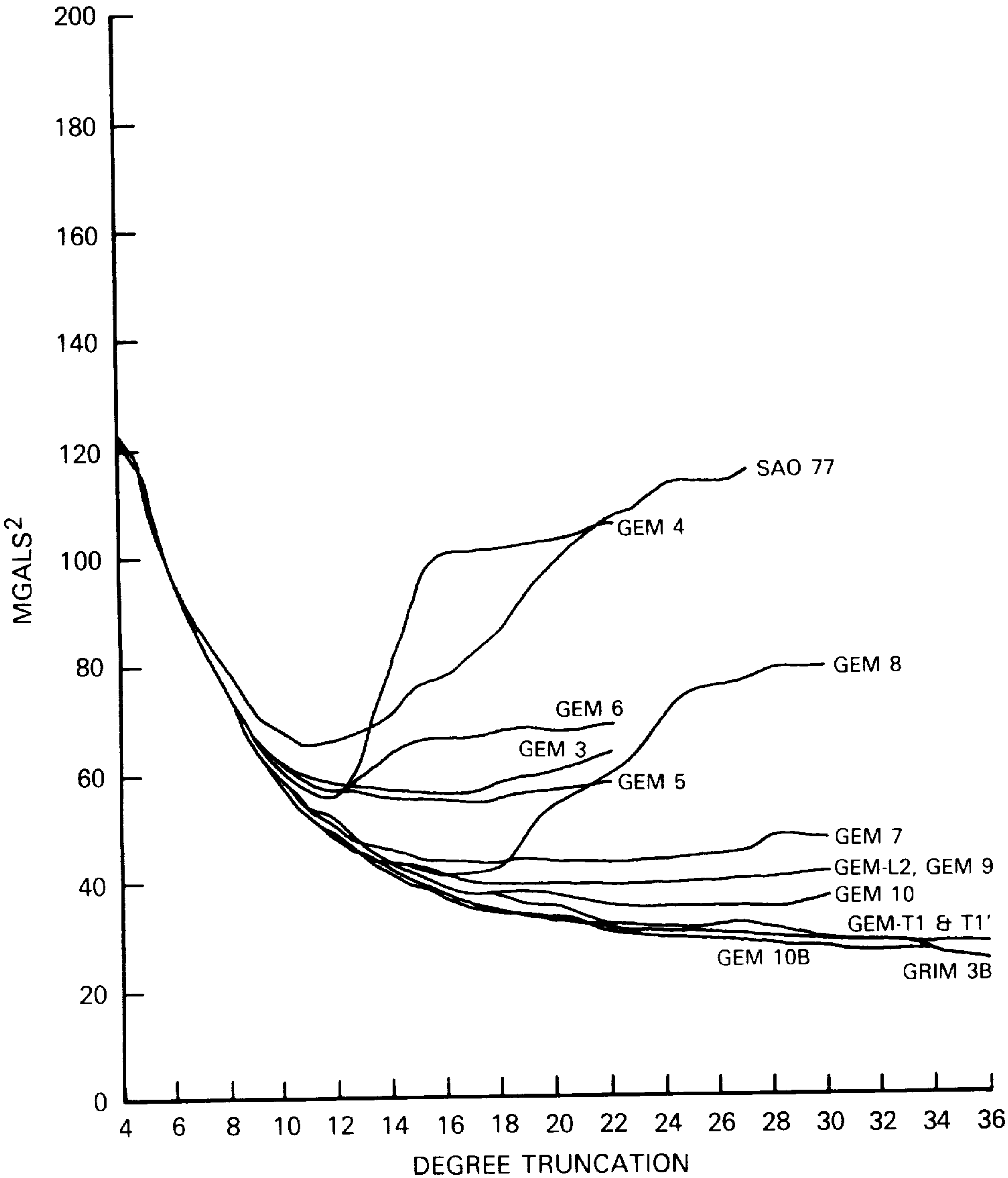


Figure II-22 Comparison of the "quality" of gravity field models developed during the past 17 years.

number of satellites. Model GEM-9, which included only satellite data, was complete to degree and order 20 (Lerch et al., 1985).

The next major advance became possible with the availability of altimeter from the GEOS-3 and Seasat missions. In the early 1980's GEM-10B (which included satellite, ground, and GEOS-3 altimeter data and was complete to order 36) was generally regarded as the most accurate gravity field model available. However, the large amount of laser ranging data acquired with Lageos-I, and the need to better determine the Lageos-I orbit for CDP measurements, led to the development of specialized Lageos-I field models. GEM-L1, developed in 1981, improved the definition of the Lageos-I orbit from one meter to 50 cm. GEM-L2, complete to degree 20, resulted in improvement in the lower order and degree terms of the spherical harmonic expansion ($L<6$) by a factor of two compared GEM-9 (Lerch et al,. 1982). This, in turn, yielded a Lageos-I orbit determination accuracy of 15-20 centimeters for 15-30 day arcs. It was quickly demonstrated that the improved field model resulted in a better determination of the orbits of geosynchronous satellites by a factor of four. The GEM-L2 field was also used to produce an early model of the large scale circulation of ocean currents from Seasat data. More significantly, the precise orbit of Lageos-I led to the detection of an acceleration of the orbit node which was attributable to a change in J_2. Improved values for GM have been obtained from Lageos (398600.440 ± 0.005 km^3 sec^{-2}) and from LLR (398600.443 ± 0.006 km^3 sec^{-2}).

Beginning in 1980, as part of the activities of the Gravsat Users Working Group, (NASA, 1980b), extensive studies were undertaken at GSFC, NGS, The University of Texas (UTX), UCLA, and Stanford University to devise new techniques for more efficient processing of gravity data and to attempt to verify the accuracies achievable with the planned Gravsat mission. These studies continued for several years with the conclusion that numerous new techniques existed which could be adapted for rapid processing of GRM data, although these methods needed to be proven through computer simulations. In 1985, UTX completed the first stage of a simulation. A numerical integration of the equations of motion was performed with an assumed gravity field (complete to degree and order 180 and including terms of degree 300 for orders 0 to 10) and other assumed initial conditions to develop a data set comparable (but noiseless) to that expected from GRM. A noise parameter was included that can be scaled and added to the observation to simulate real measurements of a specified precision. Investigators will use this data set to test the recoverability of the original field with their particular technique.

The prolonged delay in realization of the GRM, and the need for an improved field for both geophysical studies and TOPEX orbit determination, forced consideration of the development of an interim GRM gravity field model. The feasibility of an interim field was studied by a Gravity Field Workshop in 1982 (NASA, 1982b). The Workshop concluded that a factor of two, or better, improvement in the determination of the long wavelength component of GEM-10B was achievable by selective elimination of poorer accuracy data (such as Minitrack data), modification of the processing techniques, and the inclusion of newer data such as Doppler tracking and SLR data. At the same time, there was a need to convert existing, gravity and orbit determination software programs to the new supercomputers.

Work on the interim field and the software conversion to a Cyber 205 vector processing computer began in 1982. The conversion was completed in 1986: the GEODYN II and SOLVE orbit determination and geodetic parameter estimation systems are now operational on the Cyber 205. Compared to the AMDAHL V-7 the time required to calculate a one month Lageos-I arc was reduced by a factor of 18 and the time required for a SOLVE inversion of a 1921 X 1921 element matrix was reduced by a factor of 57 (Putney, 1984).

Ocean tidal models have been developed for all terms of 34 tidal constituents to reduce aliasing in the gravity field from tidal sources. More than 600 individual terms have been included in the model with a selected subset being adjusted from tracking data. This represents the first consistent multi-satellite data set for the dominant long-wavelength ocean tides.

A special field model complete to 36 x 36 in harmonics has been developed for TOPEX using a select set of 17 satellites (Marsh, 1987). This new model (GEM-T1) is compared with earlier models in Figure II- 22 and shows significant improvement over the best satellite-derived model (GEM-L2: 20 x 20 field). Surprisingly, GEM-T1', which is a model of GEM-T1 solved to GEM-L2 size, shows no significant improvement and makes evident the fact that the higher degree terms in GEM-T1 has strongly reduced the aliasing effects contained in previous satellite-derived models. The GEM-T1 model has reduced the predicted Starlette orbital error from 0.73 m to 0.23 m (Figure II-23). Applied to the TOPEX orbit, GEM-T1 predicts a radial error of 25 cm due to the gravity field uncertainty (Lerch et al., 1988). An accuracy of 10 cm is needed for mapping ocean topography. This goal is being pursued by the TOPEX Project.

In another area, an assessment was made of the capability of a spaceborne gravity gradiometer for mapping the high-frequency components of the gravity field. The influence of parameters such as orbit altitude, orbit inclination, mission duration, gradiometer precision, and sample rates were considered for evaluating uncertainties in the gravity field fine structure in terms of mean free air gravity anomalies. Consideration was given to a dedicated gravity gradiometer mission in which a gravity gradiometer would orbit the Earth in a circular polar orbit at an operational altitude ranging between 160 km and 200 km. The assumed mission duration of 180 days would give approximately 16 passes over each one degree by one degree block which translates to about 60 measurements per block. It was estimated that a gradiometer with a precision of 10^{-3}E operating at a satellite altitude of 160 km with an orbit position error of one meter can recover $1^{\circ} \times 1^{\circ}$ gravity anomalies to an accuracy of 0.5 mgal. This accuracy is reduced to 3 mgal when the recovery is made from data acquired from an orbital altitude of 200 km. Improved gradiometer precision produces a 40% to 60% improvement in the gravity anomaly uncertainty for gradiometer precisions of 6×10^{-4}E to 10^{-4}E, respectively.

2. Geoid

Satellite-borne microwave radar altimeters produce measurements of the height of the satellite above the surface. For the oceans, this is the sea surface topography. For land, it is the surface topography. The sea surface topography differs from the gravity equipotential surface, or ocean geoid, to the extent of the presence of wind and changing ocean currents. Consequently, an accurate geoid, which can be derived only from the gravity field, is essential for study of large-scale ocean circulation. The ocean geoid itself reflects the distribution of mass in the Earth's interior, and at short wavelengths may reflect the ocean bottom topography.

The first satellite altimeter measurements were obtained by Skylab in 1974, and had

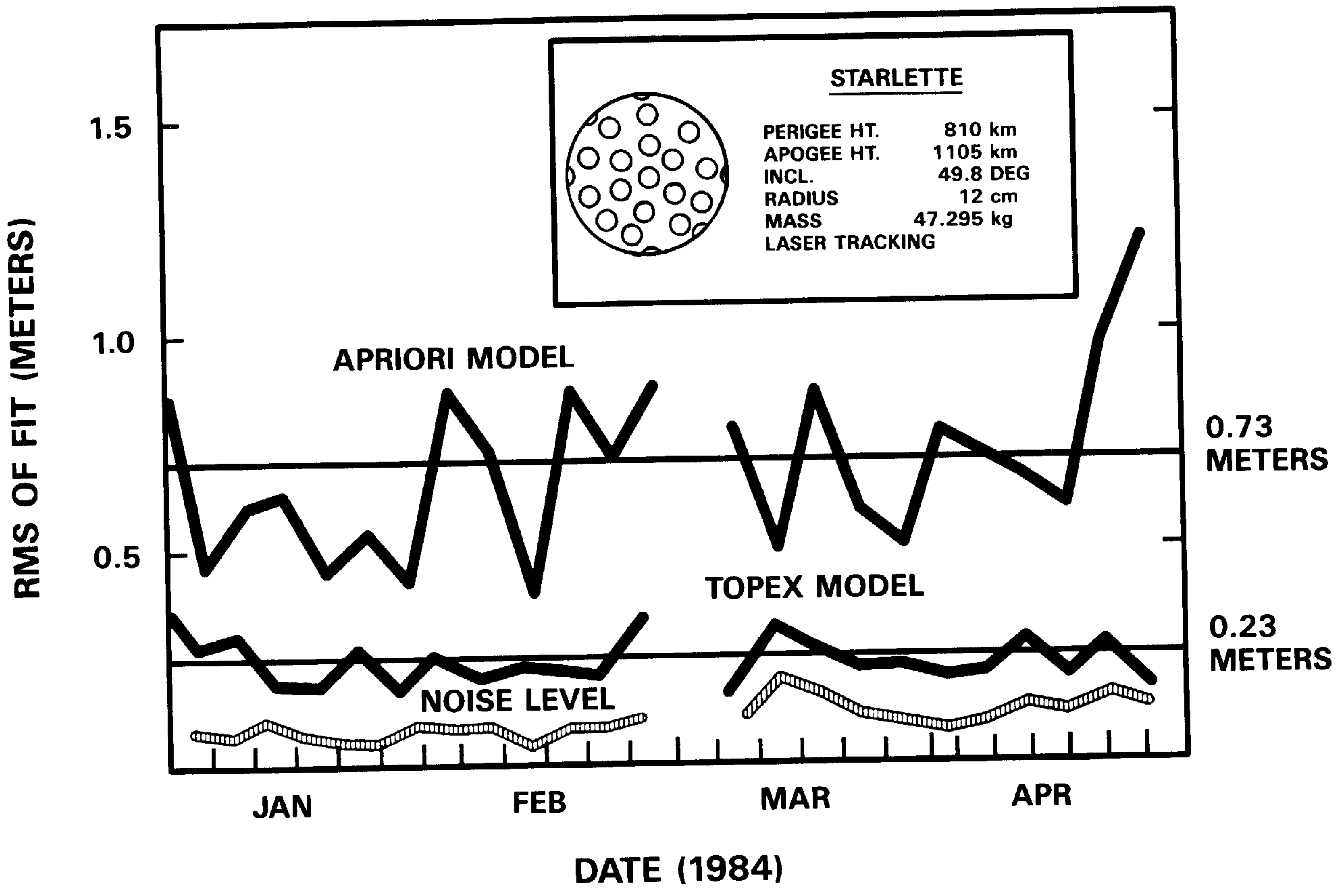


Figure II-23 Precision orbit computations for Starlette using the May 1986 TOPEX Gravity Model.

a precision of 1-2 meters. GEOS-3 (1975-1979), provided altimeter data with a precision of 20-25 cm. Seasat (1977), carried an improved altimeter. While the mission was short-lived, the Seasat altimeter produced measurements having a precision of 10-20 cm.

As a result of these missions, the sea surface topography is known globally to within half a meter, and in some areas to a decimeter or better. Thus, it is a fair conclusion that the gravity field over the oceans is generally better known than for continental areas.

The most productive information derived from these data, as illustrated by Figure II-24, is the enormous detail of ocean bottom topography and the evidence of previously unknown tectonic structures on the ocean floor (Marsh, 1985).

In addition, studies of the global geoid have shown that the observed geoid, adjusted for the slab effect of subduction zones, is in surprisingly good agreement with the geoid calculated from seismic velocity variations (Figure II-25). This illustrates that, while the broad variations of the Earth's gravity field come from a variety of sources, the bulk of the variations probably come from two types of sources: (1) density irregularities in the deep mantle, recently inferred by seismology, and (2) subduction zones, where oceanic lithosphere is recycled to the interior.

3. Tidal Gravity Field

The GEM-T1 gravity field model included adjustments of several ocean tidal amplitudes. The ocean tide solution provided amplitudes of several harmonic terms up to degree five for terms in the diurnal (K_1, O_1, and P_1), and semi-diurnal (M_2, S_2, K_2, N_2, and T_2), and long-period (M_m and M_f) bands. The second-degree solution shown in Table II-3 agrees well with the values predicted from ocean tidal models of Parke and Schwiderski. The ocean models are fits of tidal gauge data and are completely independent. This agreement between satellite amplitudes and ocean model values demonstrates that the Wahr solid Earth tidal model is probably good to 1% or better, and that the ocean tides account for at least 80% of the dissipation.

The tidal acceleration of the Moon inferred from the combined solution is -25.27 ± 0.61 arcsecond/century^2. The latest LLR solution, obtained from a fit to 16 years of data, is -24.9 ± 1.0 arcsecond/century^2 (Newhall et al., 1987). The agreement of these two independent solutions indicates that there is no significant non-tidal lunar acceleration.

4. Main Magnetic Field

Satellite measurements of the geomagnetic field began with Sputnik 3 in May 1958. The first truly global measurements were obtained by the Polar Orbiting Geophysical Observatories (POGO, otherwise known as OGO-2, -4 and -6) from 1965 to 1971.

A new era in near Earth magnetic field measurements began with NASA's launch of Magsat in October 1979 (Ousley, 1980). Magsat provided the first truly global survey of vector components of the geomagnetic field. The two principal purposes of the Magsat Mission were: (1) to provide data for modeling the main geomagnetic field at the 1980 epoch; and (2) to provide measurements of the crustal magnetic field at lower altitudes than had hitherto been achieved.

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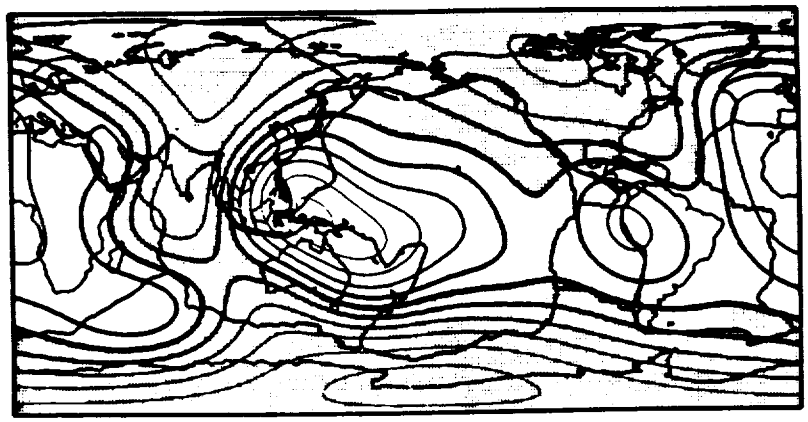
Figure II-24 Global mean sea level surface based on Seasat and Geos-3 altimeter data.



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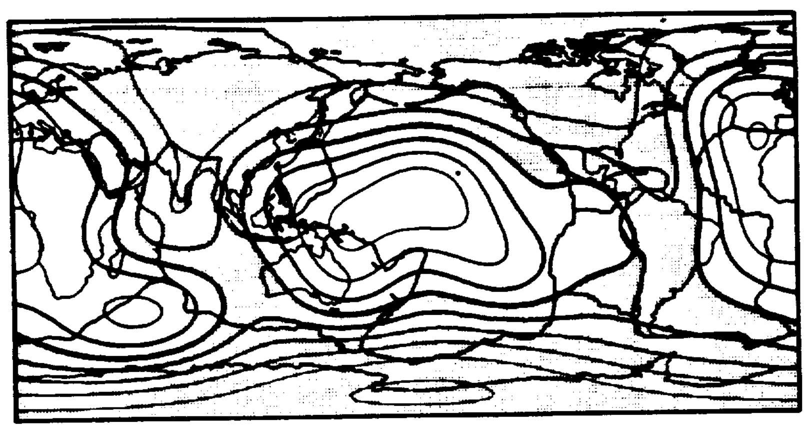
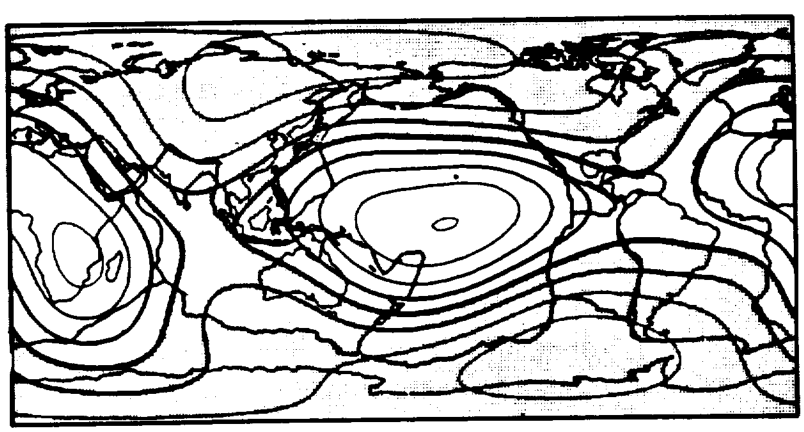


OBSERVED MINUS SUBDUCTED SLAB EFFECTS



CALCULATED FROM SEISMIC VELOCITY VARIATIONS

Figure II-25 The observed geoid, adjusted for the slab effect of subduction zones, compared with the geoid calculated from seismic velocity variations.

Table II-3

VALUES FOR DYNAMICALLY ESTIMATED 2ND DEGREE TIDES COMPARED TO OCEANOGRAPHIC DETERMINATIONS

	$C^{+}_{2m,f}$ AMPLITUDE (cm)			$\epsilon^{+}_{2m,f}$ PHASE (deg)		
	OBSERVED	OCEANOGRAPHIC		OBSERVED	OCEANOGRAPHIC	
TIDE (f)	SATELLITE	SCHWIDERSKI	PARKE	SATELLITE	SCHWIDERSKI	PARKE
LONG PERIOD (m = 0)						
M_m	.36 ± .50	1.06	----	274.10 ± 76.60	258.9	----
S_a	2.44 ± .77	----	----	31.03 ± 18.75	----	----
M_f	1.80 ± .41	1.70	----	245.35 ± 13.08	252.0	----
S_{sa}	1.68 ± .72	1.24	----	223.12 ± 26.44	221.6	----
DIURNAL (m = 1)						
K_1	2.61 ± .23	2.82	2.46	328.50 ± 5.02	315.1	312.0
O_1	2.69 ± .17	2.42	1.88	318.53 ± 3.63	313.7	309.0
P_1	0.81 ± .23	0.90	0.76	296.83 ± 16.07	313.9	311.7
SEMI-DIURNAL (m = 2)						
K_2	0.31 ± .05	0.26	----	302.14 ± 9.79	315.11	----
M_2	3.26 ± .05	2.96	3.38	320.93 ± 0.92	310.6	313.1
S_2	0.80 ± .05*	0.93	0.88	301.93 ± 3.73*	314.0	300.8
N_2	0.70 ± .07	0.65	0.58	334.01 ± 5.52	321.8	324.5
T_2	0.09 ± .05	----	----	19.76 ± 34.80	----	----

* COMBINED OCEAN/ATMOSPHERIC EFFECT

Magsat results have appeared in over 200 papers in refereed scientific journals (Langel and Benson, 1987). These include three special issues: (1) the April 1982 issue of Geophysical Research Letters (GRL,1982); (2) the 1984 Journal of Geomagnetism and Geoelectricity (vol. 36, No. 10, 1984); and (3) the February 1985 issue of the Journal of Geophysical Research (JGR, 1985).

Magsat's contribution to the understanding of the main field has exceeded prelaunch expectation. The GSFC (12/83) field model (Langel and Estes, 1985) describes the main field at 1980 to an accuracy estimated to be better than 20 nT for the main field at the surface of the Earth, including fields of low degree and order resulting from external sources. A truncated version of this model was adopted by the International Association of Geomagnetism and Aeronomy (IAGA) as the definitive International Geomagnetic Reference Field (IGRF) for 1980.

In addition to Magsat data, researchers have utilized other satellite data, e.g., POGO, and COSMOS; data from magnetic observatories; and data from land, sea and air surveys. A technique was developed (Langel et al., 1982) to solve for crustal and instrumental biases in observatory data. This technique works optimally when such data are analyzed together with satellite data.

Magsat data and models have been used in conjunction with earlier models and other data to determine the temporal change of the field. Because of the short duration of the mission, Magsat data alone is not sufficient for a good determination of the field's temporal change. Unfortunately, the distribution in time and space of the surface data are also not sufficient for a good determination. Long-term satellite data will be required if this important quantity is to be measured definitively.

Magsat models are now being utilized in studies of the field at the core-mantle boundary. They have been used to estimate the radius of the core-mantle boundary to within 2% of the seismically-determined value (Voorhies and Benton, 1982); to estimate possible fluid motion near that boundary (Voorhies, 1984); and to study the small-scale field structure at the boundary (Gubbins and Bloxham, 1985).

In the absence of definitive satellite magnetic data after Magsat, research has used surface data and lesser-quality satellite data. Using magnetic observatory data, a secular variation model based on cubic splines was derived for the 1903-1982 time period (Langel et al., 1986); this work was done cooperatively with researchers at the British Geological Survey.

Again using surface data (from observatories, land surveys, aeromagnetic surveys, and ship surveys), models were derived for epochs 1945, 1950, 1955, and 1960. These models used the spline secular variation model to project a 1980 model based on Magsat (GSFC, 12/83) backward in time to the epoch of the new model. The projected model was used as an a priori constraint on the models at the earlier epochs. Two generations of these models were derived because after the first was finished it was realized that a more definitive result could be obtained by using a more sophisticated technique of backward projection from the a priori model and by using data which had been overlooked in the first attempt. The four epoch models from the first generation set (Langel and Estes, 1987) were adopted as IGRFs by IAGA. All the second generation models were adopted by the IAGA as Definitive International Geomagnetic Reference Fields (Langel et al., 1987).

A dramatic change in the rate of change of the geomagnetic field was observed to occur at about 1970. This has been called the "geomagnetic jerk". Considerable disagreement has occurred regarding the nature of this phenomenon. Backus et al. (1987) investigated the "jerk" using data from the POGO satellite and from surface observatory data. They modeled the temporal variations with cubic, quintic, and bi-quadratic techniques.

The biquadratic model consisted of two independent quadratics, one before and one after January 1, 1970. It should give the best result if the "jerk" were really a discontinuity in the geomagnetic secular variation. The result showed almost identical goodness of fit for the biquadratic and quintic models, with an identical number of parameters, and an insignificantly poorer fit for the cubic model with substantially fewer parameters. At the high level of significance obtained, the parameters of the best-fitting biquadratic model rule out a physical model for the "jerk" in which the level surfaces of conductivity in the lower mantle are approximately spherical, and also the radial magnetic field at the core-mantle boundary goes from one quadratic time dependence to another in a year or less.

In view of the lack of definitive satellite magnetic field data since Magsat, attempts have been made to use poorer quality data to model the Earth's main field. The data used are from the Dynamic Explorer (DE)-2 and the DMSP/F-7 spacecraft. The DE-2 data suffer from incomplete knowledge of the attitude of the spacecraft which is only known to about 0.5°. The DMSP data suffer from the spacecraft field (several thousand nT) in which the body-mounted magnetometer is located. Attempts to use these data have not been successful. Neither data set has resulted in models which are sufficient-ly consistent with previous models. Further, from spectral studies of each data set, it is apparent that the noise level is such as to preclude any significant information regarding the geomagnetic field above spherical harmonic degree eleven. In contrast, Magsat data are capable of being interpreted at least to spherical harmonic degree fifty. Study of the Magsat field is continuing, and it is hoped that by employing new calibration procedures additional useful results can yet be obtained.

A definitive discussion of the history, techniques and results of analysis of the main field of the Earth has been written (Langel, 1985) and submitted to Academic Press as a chapter in Volume 1, of a multivolume series on Geomagnetism.

5. Crustal Magnetic Fields

Detection and analysis of crustal fields are complicated by the fact that they are of small amplitude at satellite altitudes so that the signal-to-noise ratio is very small. Particular difficulties arise near the auroral belts because of the intense and persistent presence of ionospheric currents. Nevertheless, maps of the anomaly field have been published for all regions of the globe.

Verification that these "anomaly fields" are indeed crustal in origin has come, e.g., from comparison with aeromagnetic data over the U.S. (Schnetzler et al., 1985) and from shipborne data over the North Pacific (LaBrecque and Raymond, 1985). While the agreement between the satellite and surface data is very good, in some regions differences exist and require further study.

The usefulness of the crustal data has been significant and extensive. Magnetic anomalies have been correlated with geological features in both continental and oceanic areas. There is a general correspondence between Magsat anomalies and similar geologic structures. For example, large-amplitude anomalies (>20 nT) are found over oceanic plateaus and many continental shields, as well as active and passive rifts.

A comparison between magnetic anomalies and some geological features in Canada and the northern U.S. (Fig. II-26) shows a close correlation between these data (Arkani-Hamed et al,. 1985). Basins such as the Michigan (M), Thelon (T), the NE British Columbia Basin (B) and the Eagle Plain (E), are positive magnetic anomalies in this map. The long positive anomaly located between 35°N - 100°W and 45°N - 80°W is parallel to the Mid-Continent Rift Zone, but is displaced southward. On the other hand, the northern part of the Appalachian and Cordilleran orogens, as well as the Greenville-Superior suture zone have negative magnetic anomalies. This is also the case in the Labrador Sea and Hudson Bay. The largest anomaly in the U.S. is located in Kentucky and has been associated with a large intrusion which also exhibits a significant gravity anomaly (Mayhew et al., 1982).

Mayhew (1985) has used satellite magnetic data as an aid to mapping the Curie isotherm depth. He shows that in some regions the anomaly pattern directly reflects change in that depth.

For oceanic crust a seafloor-spreading model has been developed which explains the major anomalies seen in the Magsat data of the northern Atlantic (Labreque and Raymond (1985). The seafloor spreading anomalies of the North Atlantic Basin conform to the strike of the continental margins and the spreading axis. The major crustal isochrons of the North Atlantic are displayed in Figure II-27. It can be seen that the Magsat anomalies are collinear to these isochrons which represent times of significant change in the geomagnetic reversal rate. The Jurassic and Cretaceous quiet zones were generated during periods of predominantly normal geomagnetic polarity which lasted for 10 and 30 million years, respectively. The quiet zones record a period of stability in the geomagnetic field; however, the ocean crust associated with the later M sequence and the Cenozoic sequence record a geomagnetic reversal on the order of two to four reversals per million years.

Forward modeling has been undertaken in several regions. This type of model is less complicated for relatively isolated individual anomalies. Two such anomalies are located at the Lord Howe Rise and Broken Ridge submarine plateaus. The Lord Howe Rise is generally accepted to be submerged continental crust. Modeling the contrast between the Lord Howe Rise and the surrounding region, Frey (1985) showed that, if the rise is continental crust, then the lower crustal layer has probably been replaced or altered to a rock type with high susceptibility. Johnson (1985) was able to model Magsat data over the Broken Ridge, assuming magnetization parallel to the present-day field. While unable to distinguish between several classes of models, he concluded that the magnetization over the ridge has been enhanced by viscous remanent magnetization. Taylor and Frawley (1987) used magnetic component data from Magsat in their study of the Kursk Magnetic Anomaly. Using two different methods, they found that a component of remanent magnetization was influencing this anomaly. Remanent magnetization cannot, therefore, be excluded in Magsat anomaly interpretation.

Forward models have been derived for several subduction zones: the Aleutian, Middle America, Kuril, and New Hebrides Trenches (Clark et al., 1985; Vasicek et al.,1987). These three-dimensional model studies show that peak anomaly amplitude and

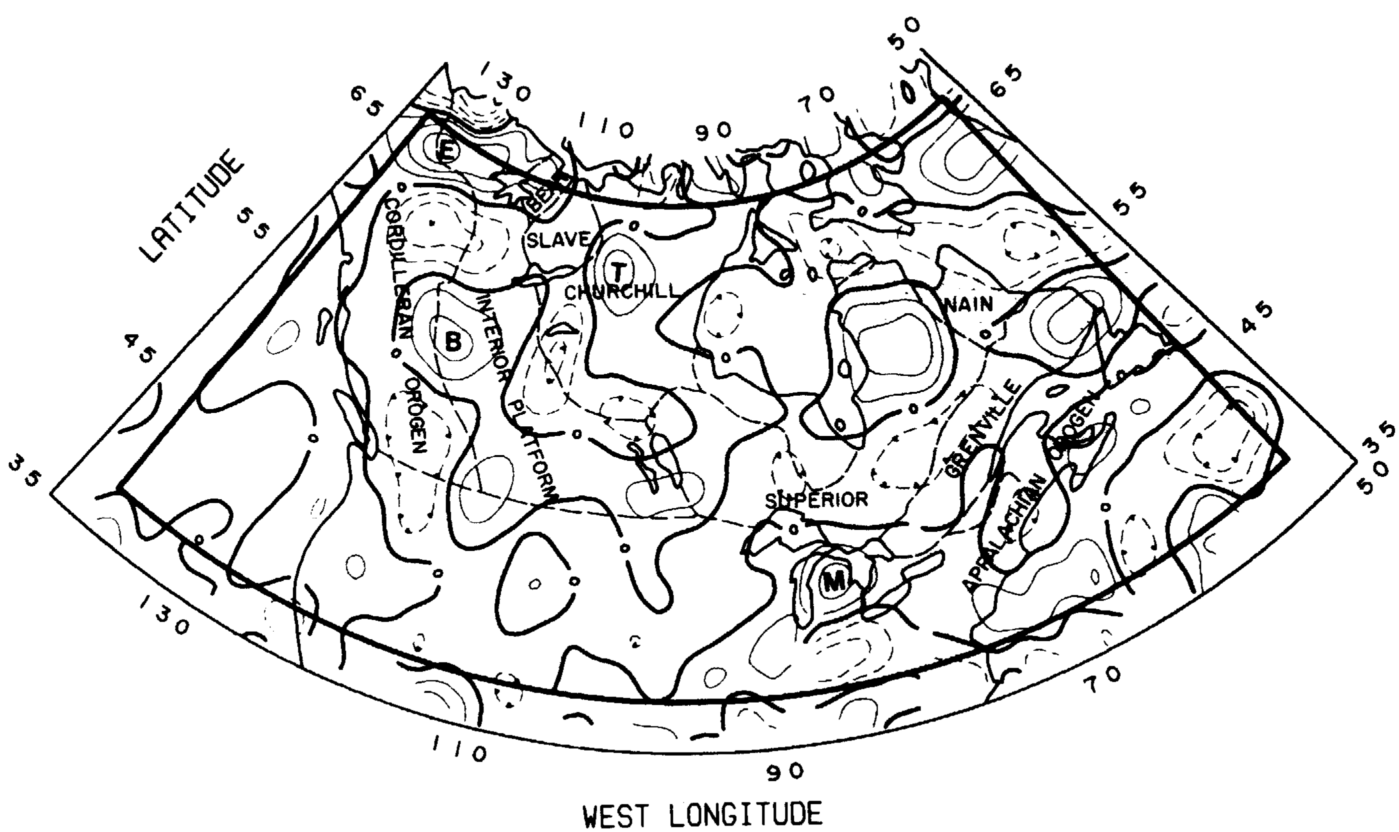


Figure II-26 Comparison between magnetic anomalies and some geological features in Canada and the northern U.S.

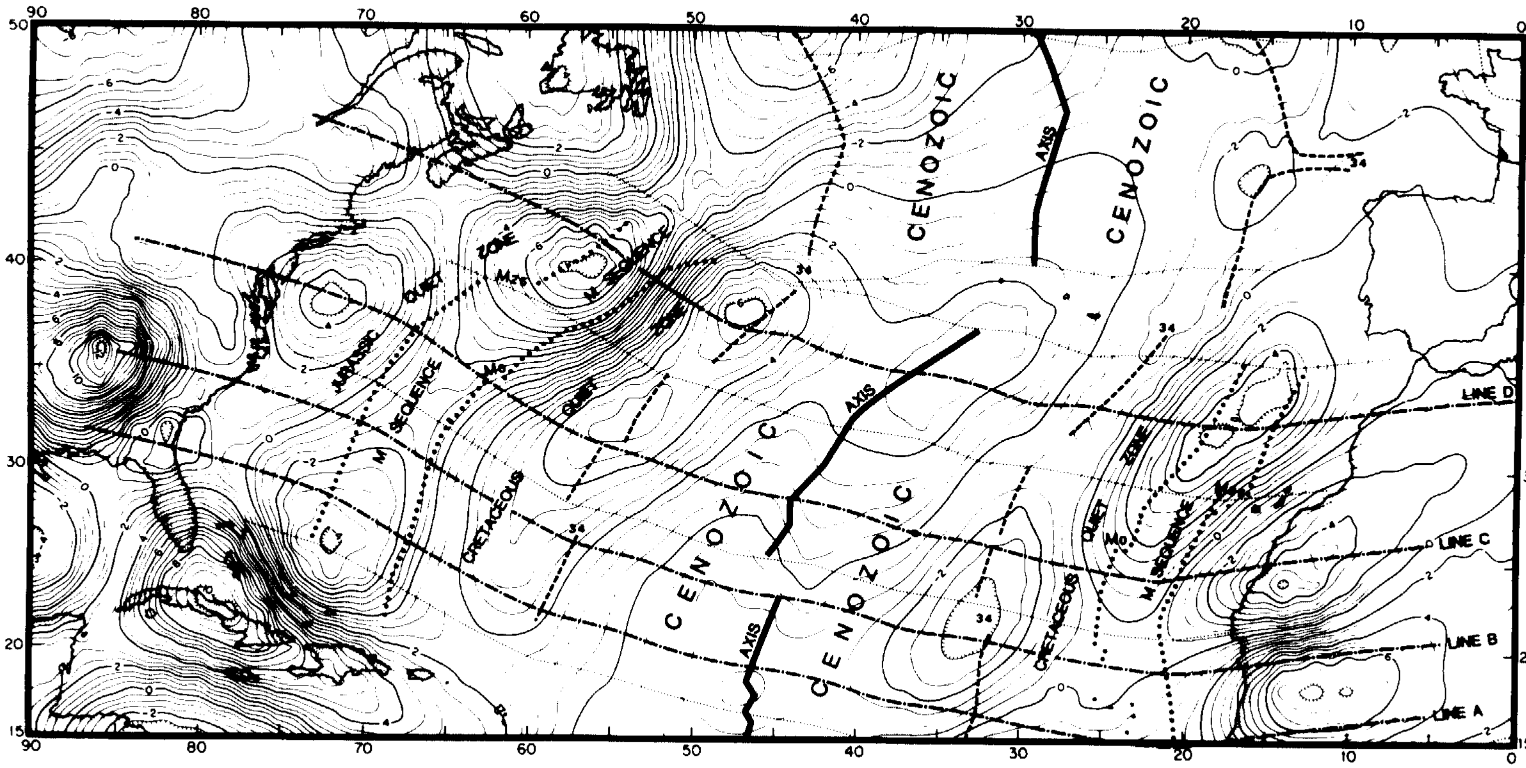


Figure II-27 Contour map of the North American Magsat field and major isochrons of the North American crust.

location depend on slab length and dip. In all cases the reduced-to-pole Magsat anomaly data (i.e., data transformed to the form it would have if the inducing field were everywhere vertical) are reasonably well reproduced with a slab thickness of 7 km and combined induced and viscous magnetization of four amperes per meter in a 50,000 nT inducing field.

An extensive effort has been made to derive analytic representations of the crustal fields which permit reduction to common altitude, reduction to the pole, and calculation of some equivalent magnetization, given some assumptions about the thickness of the magnetic layer, etc. Methods for accomplishing this with aeromagnetic and shipborne data have been known for some time. However, because of the limited area covered by such surveys, these solutions assumed a flat Earth and a constant main geomagnetic field. Extension of these results to satellite data was begun by Bhattacharyya (1977) and by Mayhew (1979). Mayhew's method has proven most useful, except that near the equator the solution becomes unstable. A way of overcoming this instability was devised by Langel et al (1984). Using basically the same method but with two-degree averaged data as input, von Frese et al. (1981, 1982) have been able to obtain reductions to the pole both at middle (1981) and at low latitudes (1982).

Proper interpretation of magnetic anomaly maps must be guided by the mineralogy of the crust and upper mantle. Wasilewski et al. (1979) have indicated that the mantle is non-magnetic, i.e., that unless the Curie isotherm is within the crust, the lower boundary for the magnetic layer is the Moho. Curie points and magnetization values for lower crustal xenoliths (thought to be probable components of the lower continental crust) were studied by Wasilewski and Mayhew (1982). Three tectonic features were represented: converging plate margins, rift valleys, and continental intraplate regions. Their study showed that metabasic rocks in the granulite facies have magnetization values consistent with that inferred from models of long-wavelength anomalies. They conclude that, for at least some tectonic features, the lower crust may be the most magnetic layer. This is substantiated by Wasilewski and Fountain (1982) in a study of the Ivrea Zone of northern Italy and by Schlinger (1985) in a study of the magnetic mineralogy and magnetic properties of rocks from Lofoten and Vesteralen, Norway, a province of deep-seated origin.

Hinze and von Frese (1987) conducted a statistical study of the Magsat anomalies over the continents and the oceans and found that the mean magnetic anomalies were statistically greater for the continents.

Although not a part of geodynamics proper, the Magsat data was used to study magnetic fields from external sources. In particular, Maeda et al. (1982) reported a newly discovered meridional current and mapped its characteristics (Maeda et al., 1985). Takeda and Maeda (1983) have described an F-region dynamo which would account for the measurements.

The analysis of Magsat data is expected to continue. However, more substantive progress on secular variations and detailed analysis of crustal features will require higher spatial resolution data and the extended duration data from the MFE and Magnolia missions.

III. SYSTEMS AND MODELING DEVELOPMENT

A. SATELLITE LASER RANGING

The development of SLR systems within NASA started in the early 1960's soon after the invention of the laser. Originally developed to improve the precision of orbital tracking of satellites, SLR has been applied to the determination of station position, baseline lengths, polar motion and Earth rotation, and to studies of solid Earth tides. In the past twenty years, about a dozen satellites equipped with cube corner retro-reflectors have been launched by the U.S. and other countries. Meanwhile, laser ranging precision has improved rapidly from the meter levels of the early 1970's to sub-decimeter-level systems in 1979, and to sub-centimeter levels in 1987.

SLR has also evolved into several different types of systems. These include: (1) observatory-class systems which were designed and installed as permanently-fixed stations; (2) trailer-mounted systems, like Moblas, which were designed to be moved between sites but which were eventually located at semi-permanent sites; and (3) highly mobile systems, like the TLRS or MTLRS, which were designed for air transportation and rapid (few day) movement between sites. Table III-1 compares the system design features of the U.S. systems. Figure III-1 shows the location of the global Network of fixed stations and Table III-2 lists station precision for single-shot ranging to Lageos-I.

1. Permanent SLR Stations

a. Moblas Systems

The first Moblas was built at GSFC in 1967. In this first-generation system, the laser transmitter and receiver were mounted on a Nike-Ajax mount which could be moved between sites that provided a weather shelter for the laser system. The rest of the laser ranging system electronics were housed in a single van.

Moblas-2 was built in 1971. In this second generation system, all the instrumentation for the operation was located in a single van, including the laser system, the receiver electronics, the computer, and the control electronics for the mount and the data storage system. The pointing system was made an integral part of a trailer that could be towed by a standard tractor.

Moblas-3 was built in 1975 and was similar to Moblas-2 except that it used two vans: one for the laser and pointing system and one for the computer and receiver signal processor (later Moblas-2 was modified to be similar to Moblas-3). For these stations, the laser was located on a fixed optical bench within the trailer. The output beam was directed up to the pointing platform by a series of flat mirrors, collimated by a small telescope, and transmitted to the satellite. After being set up on a concrete pad, the mount and laser bench were isolated from the trailer and supported directly from the pad by attaching legs. The receiver was mounted at the prime focus of the large telescope.

All three early Moblas stations demonstrated high reliability and decimeter accuracy; and through the mid-to-late 1970's were the state-of-the-art in mobile laser ranging systems. These systems were deployed, beginning in 1972 and every two years thereafter, in California and Utah for the SAFE measurements.

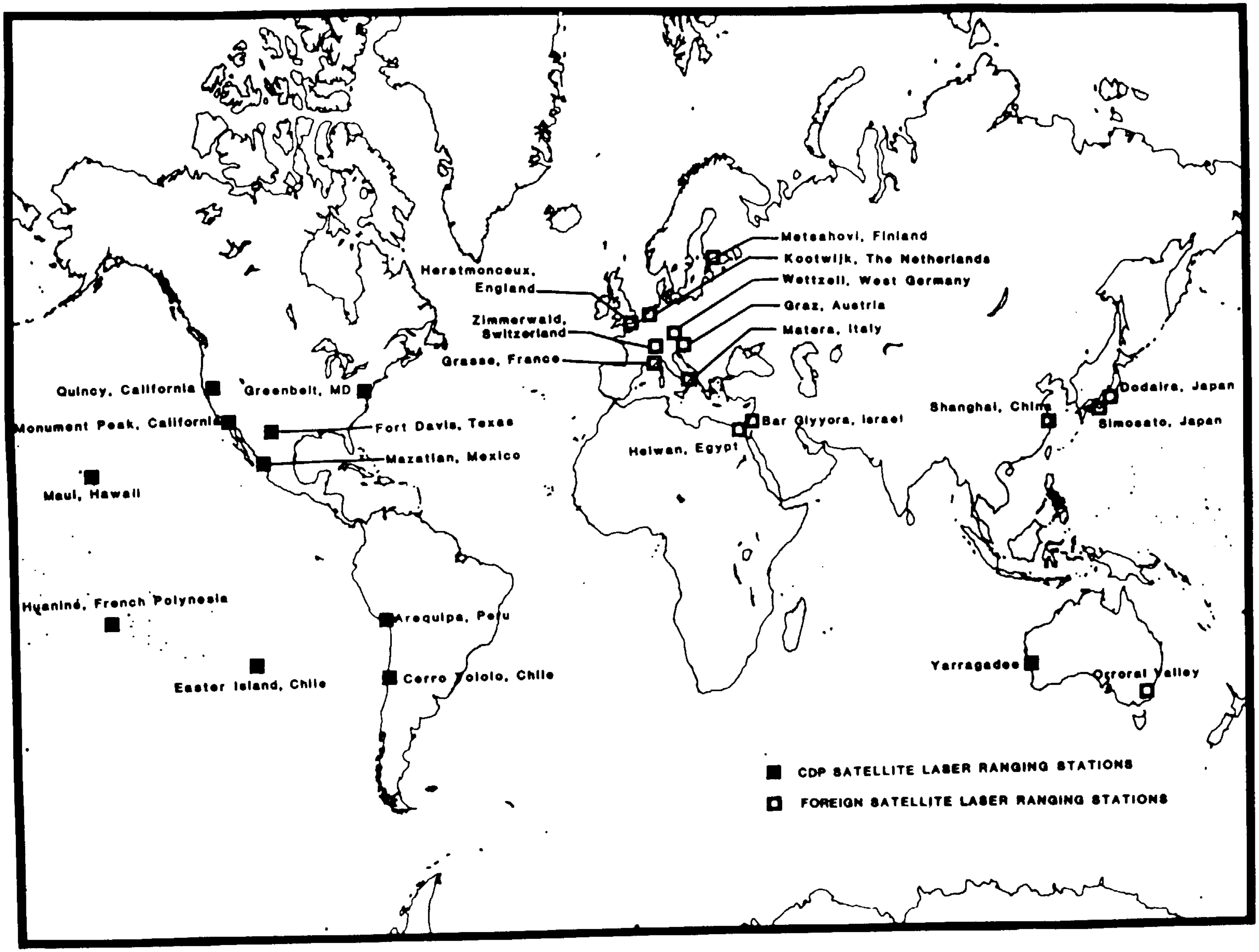


Figure III-1 Fixed Satellite Laser Ranging stations: September 1987.

TABLE III-1.

SLR SYSTEMS COMPARISON

	MOBLAS (7)	TLRS-1	SAO (UPGRADED)	TLRS-2
Wavelength (nm)	532	532	694	532
Power-Energy/ Pulse (mj)	100	100	300	20
Pulse Repetition Rate (pps)	5	5	0.5	10
Divergence (mrad)	0.1	0.2	0.6	0.1
Receiver Sensitivity (Photons)	60	15	100	1
Pulse Width (psec)	200	200	600	200
Receiver Diameter (cm)	75	30	50	28
Range Accuracy* (cm)	0.7	1.5	15	3

*Single Shot

TABLE III-2
SLR STATION PRECISION (1987)

Station Location	Precision (cm)*
Monument Peak, California (MOBLAS-4)	1
Yarragadee, Australia (MOBLAS-5)	1
Mazatlan, Mexico (MOBLAS-6)	1
GSFC, Maryland (MOBLAS-7)	1
Quincy, California (MOBLAS-8)	1
Haleakala Observatory, Hawaii	3
McDonald Observatory, Texas (MLRS)	4
Arequipa, Peru (SAO-2)	15
Orroral Valley, Australia	4
Matera, Italy (SAO-1)	14
Wettzell, FRG	4
Kootwijk, Netherlands	20
Grasse, France	3
Graz, Austria	3
Herstmonceux, England	5
Zimmerwald, Switzerland	7
Shanghai, China	13
Metsahovi, Finland	20
Dodaira, Japan	50
Simosato, Japan	3
TLRS-1	1
TLRS-2	3
MTLRS-1 & -2	5

*Single-shot ranging to Lageos

In mid-1979, third generation systems (Moblas 4 through 8) became available. These systems were functionally quite similar to Moblas 1-3, but incorporated additional reliability and maintenance features and significant improvements in the optical, mechanical, and pointing subsystems.

During 1979, seven Moblas stations were deployed in the U.S., Australia, and the Pacific, and together with fixed laser stations formed the initial global network of lasers. These were used to track Seasat, to maintain the accuracy of the Lageos-I ephemeris, to monitor polar motion and Earth rotation, and to begin studies of tectonic plate motion and plate stability.

At the beginning of the CDP, Moblas stations were located at GSFC; Haystack, Massachusetts; Ft. Davis, Texas; Owens Valley, California; Goldstone, California; Kwajalein, Marshall Islands; American Samoa; and Yarragadee, Australia. A Moblas was also co-located with the fixed laser at the LURE Observatory at Mt. Haleakala, Maui, Hawaii, and remained there while the Hawaiian laser operations were interrupted for refurbishment and upgrade of the facility.

In 1981, Moblas-7 (Figure III-2) replaced the aging stationery laser (Stalas) at GSFC. Moblas stations were established at Platteville, Colorado; Monument Peak, California; and at a new location at the Quincy site in California. The SLR capability at Mt. Haleakala, Hawaii was improved and after extensive collocation with Moblas-1, the station was returned to operational status.

Two-centimeter, single-shot, precision was demonstrated using Moblas-4 with a Quantel laser. The Quantel laser, with a pulse width of 200 ps, was a significant improvement over the 7 ns pulse width of the previous laser, and proved to be reliable for both daytime and nighttime tracking. This new laser and the new receiver components (photomultipliers, gating circuits, amplifiers, time interval units, and discriminators) appeared to be the best way to optimize performance of the narrower-pulse Quantel laser. Based on this performance, the Quantel laser was selected for the upgrading of Moblas 5-8 in 1983.

A Moblas was sent to Mazatlan, Mexico (Moblas-6), and Huahine, French Polynesia (Moblas-1), in 1983. Others remained in Australia (Moblas-5); Monument Peak, California (Moblas-4); Quincy, California (Moblas-8); and GSFC (Moblas-7). In addition, the Global Laser Network was extended through cooperative data exchange agreements with other countries operating SLR systems. These included: The Federal Republic of Germany, The Netherlands, France, Italy, England, Austria, Japan, and China. During the 1983-1984 MERIT campaign, SLR data were also exchanged with Czechoslovakia and the USSR.

In 1985, Moblas-2 was provided on indefinite loan to the Israeli Space Agency for establishment of the Bar Giyyora Station; Moblas-1 at Huahine was decommissioned; and Moblas-3 was mothballed. In all, twenty years after the first SLR observations, data are now being acquired by 22 systems in 17 countries.

In 1986, Moblas-7 was upgraded by replacing the conventional photomultiplier tube with an ITT MicroChannel Plate (MCP) photomultiplier tube, changing to a Tennelec Discriminator, using the HP 5370B Time Interval Unit, adding parallax correcting optics for calibration with new short-range targets on Nelson piers, and adding internal calibration capability. This new Moblas-7 system has a single-shot rms error of 7 mm

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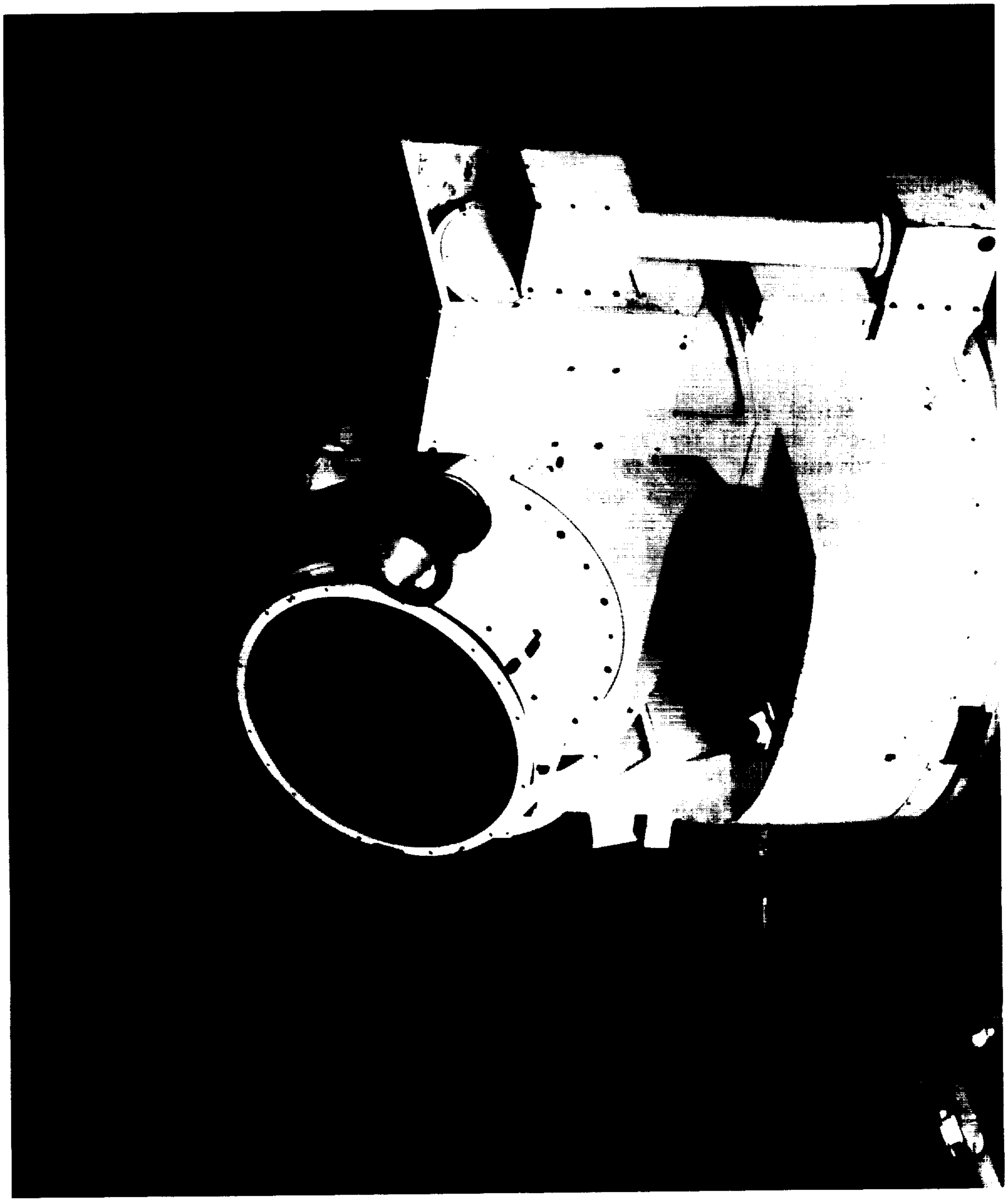

Figure III-2 Mobile Laser Ranging Station (Moblas-7).

and systematic errors can be calibrated to the 2 mm level. Similar upgrades of Moblas-4, -5, -6 and -8 were started in 1987 with the installation of the MCPs and the Tennelec Discriminators. The calibration upgrades will be completed in 1988.

b. SAO Systems

The SAO, under contract to NASA, participated in the development and use of satellite laser ranging systems beginning in 1965. A prototype of the SAO lasers was established in Mt. Hopkins, Arizona, in 1967. In addition to laser operations through 1979 (Pearlman et al., 1978 and 1982), this station was used for a test bed for engineering modifications. SAO laser stations were located in Arequipa, Peru; Natal, Brazil; and Orroral Valley, Australia. However, only the Peru Station and a station on loan to Italy are currently in operation: the Peru SAO Laser will be replaced with a TLRS in 1988.

2. Transportable Laser Ranging Stations

a. TLRS-1

Soon after the initial deployment of Moblas systems, it became evident that the approximate two month interval for moving between sites was a severe limitation which reduced the effectiveness of SLR for regional crustal deformation measurements. In 1977, a highly mobile LLR system under development by the University of Texas at Austin was re-directed to produce the first highly mobile SLR system. Designed to use a low-power laser, TLRS-1 operated in the single photoelectron regime for return pulses with a ranging precision of 2 cm for one-minute normal points (10 cm single shot rms). It was designed to be truck-mounted and air transportable.

TLRS-1 began field operations in 1981. In 1982, TLRS-1 visited Mt. Hopkins, Arizona; Vernal, Utah; Ft. Davis, Texas; and Owens Valley, California, producing 72 measurements of regional deformation baselines to and between SLR base stations in western North America. In 1983, TLRS-1 traveled to Yuma, Arizona; Quincy and Monument Peak, California; and Bear Lake, Utah. In 1984, the system was flown to Chile for measurements at Santiago and Cerro Tololo.

In late 1984, during collocation tests preparatory to a laser upgrade, a systematic pointing-dependent range bias of about 12 cm was discovered. This was traced to the photomultiplier tube, which had a variable time delay dependent on the location of the image spot on the photo surface. This was fixed by replacing the old tube with a MCP tube. At the same time, it was decided to completely upgrade TLRS-1 to the high accuracy configuration being implemented on Moblas-7. The laser power was raised to 100 mj; the change to MCP, Tennelec Discriminator, and HP 5370B Time Interval Unit was implemented; internal calibration was upgraded; and range calibration to short- and long-range targets was added. This upgrade eliminated the systematic bias and improved (by a factor of eight) the single-shot (rms) ranging precision for Lageos-I measurements, to 1.3 cm. In collocation, TLRS-1 agreed with Moblas-7 at the millimeter level. This work was completed in 1986, and TLRS-1 was deployed in early 1987 to the Mediterranean to participate in the WEGENER Medlas measurements. A photograph of TLRS- 1 with its support trailer is shown in Figure III-3.

Figure III-3 Transportable Laser Ranging Station (TLRS-1).

b. TLRS-2

Development of TLRS-2 was initiated by GSFC in 1979. This second- generation TLRS employs modular construction, a low-power laser, and single-photon detection techniques to meet the rapid deployment, high-precision tracking requirements of the CDP. It is packaged in shipping containers that will fit in the cargo hold of small commercial passenger jet aircraft.

TLRS-2 became operational in 1982. It successfully completed a data acquisition campaign at Easter Island, and was moved to Otay Mountain, California, in August 1983. At Otay, it acquired data to remeasure the relative position of this site with respect to Monument Peak and Quincy, California, key sites in the SAFE. In March 1984, after a short period at Cabo San Lucas, Mexico, the system returned to Easter Island.

In 1984, TLRS-2 was returned to GSFC for upgrading. The laser power was increased, the MCP and the Tennelec Discriminator were installed, and new calibration procedures were developed. Collocation testing was completed in early 1987, and TLRS-2 agreed with Moblas-7 at the millimeter level.

TLRS-2 was deployed to Huahine Island as a replacement for Moblas-1 on a six-month basis. In late 1987, it moved to Easter Island for six months. It will continue to shuttle between Easter Island and Huahine, spending half of each year at each site.

c. TLRS-3 and -4

Development of TLRS-3 and TLRS-4 began in 1983. The original system design was patterned after TLRS-2. However, because of the field experiences with TLRS-2, the housing design was changed to enclose the entire system in an environmentally-controlled, room-size shipping container. The telescope extends through the roof into a protective dome. Recently, it was decided to include in TLRS-3 and -4 the system upgrades applied to Moblas-7, and TLRS-1 and -2. TLRS-3 and -4 are now expected to be operational in early 1988. It is planned that one of these systems will spend part of its time in Peru as a replacement for the SAO laser at Arequipa, and part of its time in Cerro Tololo, Chile. The other system will resume measurements in the western U.S. which were discontinued in 1984 because of the need to investigate the TLRS-1 ranging problem.

d. MTLRS-1 and-2

The Modular Transportable Laser Ranging System (MTLRS) shown in Figure III-4 was designed and built by the Institute of Applied Physics, Delft, Netherlands, in cooperation with IfAG of the FRG. MTLRS-1 is owned by IfAG and MTLRS-2 is owned by The Delft University of Technology. The principal feature is a roll-out laser/telescope system supported by an electronics van. In shipment, the laser/telescope is stored in the van (see Aardoom and Wilson, 1983).

MTLRS-1 was completed in 1984 and sent to the U.S. for collocation testing at GSFC. In late 1985, it was returned to Europe for collocations at Wettzell, FRG, and Matera, Italy, and to begin Medlas measurements at Italian sites.

MTLRS-2 was completed in early 1985. It conducted measurements in Switzerland and was also collocated with the Wettzell and Matera lasers.

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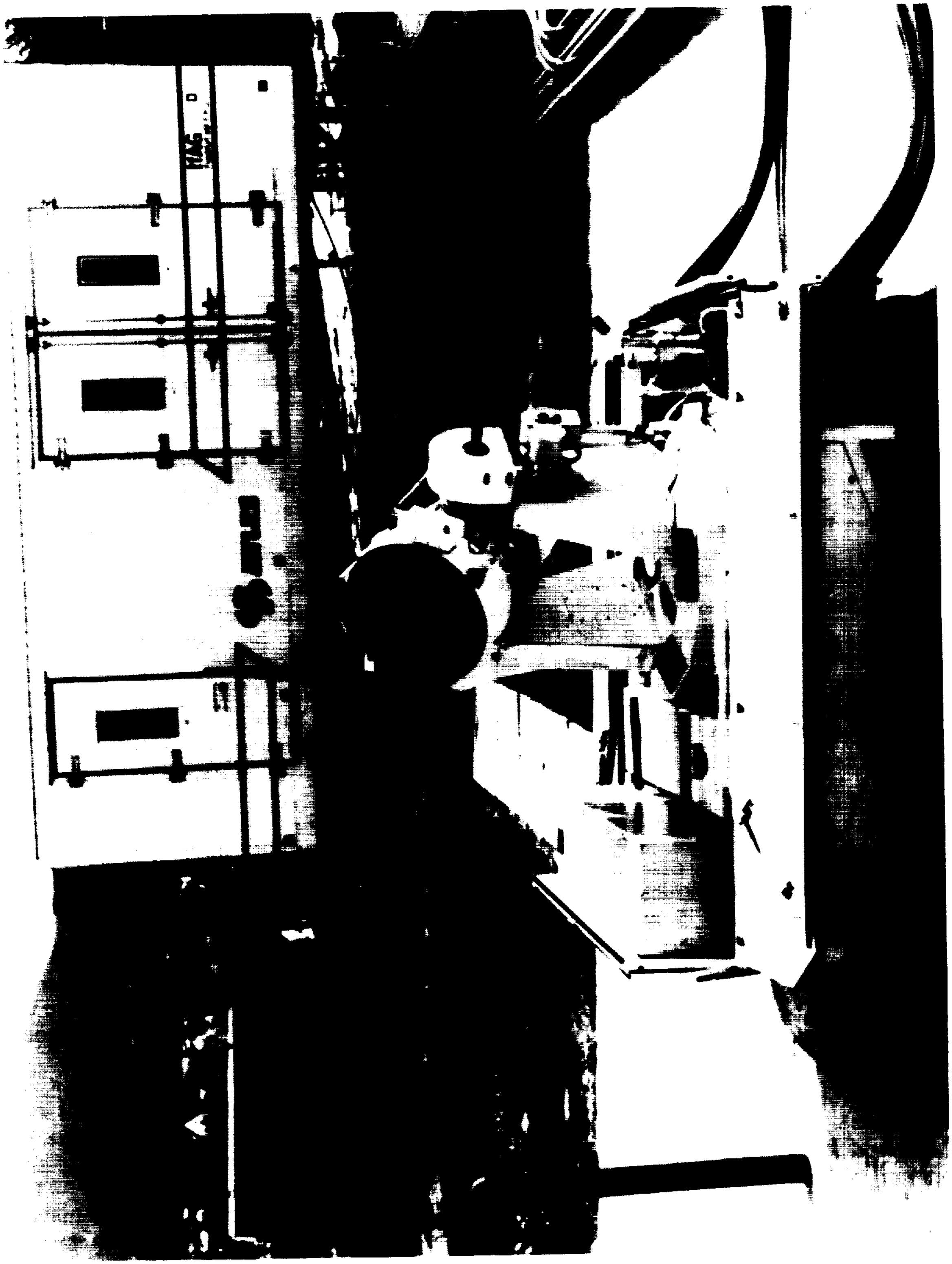

Figure III-4 Modular Transportable Laser Ranging Stations (MTLRS-1).

MTLRS-1 and -2 began measurements in Greece in early 1986. These measurements were extended to include Turkey when TLRS-1 arrived in Europe in early 1987.

TLRS-1 returned to the U.S. at the end of 1987, and is to be joined in 1988 by the MTLRS-1. The two laser stations will conduct a series of measurements in the eastern and western portions of the U.S. during 1988. TLRS-1 is also planned to visit sites in Baja California. In 1989, the two will return to Europe. Thereafter, they will alternate between Europe and the U.S., spending one year in each area.

3. Lunar Laser Ranging

LLR was conceived in the late 1950's when the gravitational research group at Princeton University showed that precision tracking of a high-altitude satellite against the stellar background could be used to measure possible changes in the gravitational constant (Dicke et al., 1961). The usefulness of such a technique not only for relativity studies but also for lunar science, celestial mechanics, and lunar and terrestrial geodesy, led the U.S. and the USSR to place retroreflectors on the Moon. The Lunar Ranging Experiment (LURE) retroreflectors (see Bender et al., 1973) were installed by the crews of Apollo 11, 14, and 15. Two other French retroreflectors were emplaced by the Soviet Luna 17 and 21 missions. A summary of the accomplishments of fifteen years of LLR is given in Dickey et al. (1985).

The LLR data provides information in a number of fields. These include the geodynamics of the Earth-Moon system, the lunar orbit, and fundamental tests of gravitational theory. Of importance to the geodynamics community has been the series of measurements permitting long-term studies of variations in the Earth's rotation, as well as determination of many parameters of the Earth-Moon system. The coordinates of the observatories are determined in the geocentric frame. LLR provides an accurate value of the principal term, GM, in the Earth's gravity field. Secular acceleration of the Moon determined from LLR analysis has implications for ocean tides, the decrease in spin rate of the Earth, and the evolution of the lunar orbit.

The LLR observations are two to three orders of magnitude more powerful than previous optical methods for determining the position of the Moon. The improved lunar data have been used to construct an ephemeris which gives the position of the Moon to within about 2 meters bias, 5 meters orientation, and a few centimeters in range. This ephemeris models many effects which had not been previously incorporated into lunar theory, such as relativity, the low degree lunar gravity field, and low degree zonal harmonics of the Earth's gravity field. Smaller effects recently added to the models include solid-body tides on the Moon and the interaction between the Earth's oblateness and the Sun.

Both the lunar Love Number, k_2, and the lunar solid friction (Q) are solution parameters in the model. Although the K_2 obtained agrees reasonably well with theory, the Q obtained is unexpectedly small. An alternative explanation for this result is that the libration signature results from viscous coupling with a small lunar core. The position of the retroreflectors, in selenocentric coordinates, is known to a few meters, while the relative position of the retroreflectors is known to about half this amount. These positions are key control points in the lunar cartographic system. Verification of the Principle of Equivalence for massive bodies was achieved by seeking the Nordtvedt effect in the lunar orbit; this contribution to fundamental physics gave the first test of the nonlinear and dynamical structure of General Relativity's post-Newtonian field components.

For the first fifteen years, the lunar system which used the 2.7-meter telescope at the University of Texas' McDonald Observatory was the only facility which obtained regular observations. Current operational LLR facilities are located at the McDonald Observatory (McDonald Laser Ranging Station - MLRS); the LURE Observatory on Mt. Haleakala, Hawaii; and Grasse, France. The design features of the MLRS and Haleakala Stations are listed in Table III-3.

Overall, there are five stations that are either acquiring, or are planning to acquire, lunar data. Achieving centimeter-level precision is a common goal, and improvements to these stations are continuing: modifications to the receiver telescope are underway at the Haleakala Station; the MLRS is to be re-located to a new site; improvements to the Grasse facility were successful in providing LLR data of decimeter accuracy in 1984 and 5 cm in 1987; a new SLR system at Wettzell, FRG, is planned to have LLR capability; upgrade of the LLR facility in Australia is continuing. Figure III-5 traces the improvements in LLR data quality for the past five years.

a. MLRS

Initially, LLR observations at the McDonald Observatory made use of the 2.7 meter telescope, the tenth largest astronomical telescope in the world. In late 1979, a NASA contract was implemented with the University of Texas at Austin, which operates McDonald Observatory, for fabrication of the MLRS. This station, to be permanently located at McDonald Observatory was to be capable of ranging to the Moon and to Lageos with a normal point precision of 3 cm. The MLRS was partially derived from equipment developed for a station which was intended to provide mobile LLR capability (see Shelus, 1985).

The MLRS (Figure III-6) established Lageos-I ranging capability and underwent collocation testing with TLRS-1 in 1982. There were some problems with lunar ranging, and several improvements were made, including changing to a short-pulse (200 ps) laser. By June 1985, the lunar capability was established with MLRS, and the old system on the 2.7 meter astronomical telescope was decommissioned. The performance of MLRS at this stage was 6 cm single-shot (rms) to Lageos-I and 5 cm normal point (rms) on lunar targets. However, the astronomical seeing at the MLRS site adversely affected the amount of LLR data that could be acquired. Thus in 1987 it was decided that the MLRS should be moved to a new location at McDonald Observatory where the seeing is considerably better. Concurrent with the move, upgrades will be implemented to improve the Lageos ranging accuracy to the subcentimeter level and to improve LLR accuracy to the centimeter level.

b. Haleakala Observatory

The LURE Observatory on Mt. Haleakala, Maui, Hawaii, is operated by the Institute of Astronomy of the University of Hawaii. The system uses a 40.6 cm coelostat-configured telescope for transmitting pulses generated by a Nd:YAG laser, and for receiving pulses reflected from Lageos-I. Pulses reflected from lunar retroreflectors are received by a novel type of telescope designed and constructed by the University of Colorado and the National Bureau of Standards. The lunar ranging system (Figure III-7) contains an array of 79 lenses (19.4 cm) mounted in a rigid structure on a tracking mount (the equivalent collecting area of a 173 cm clear aperture). Mirrors are used to

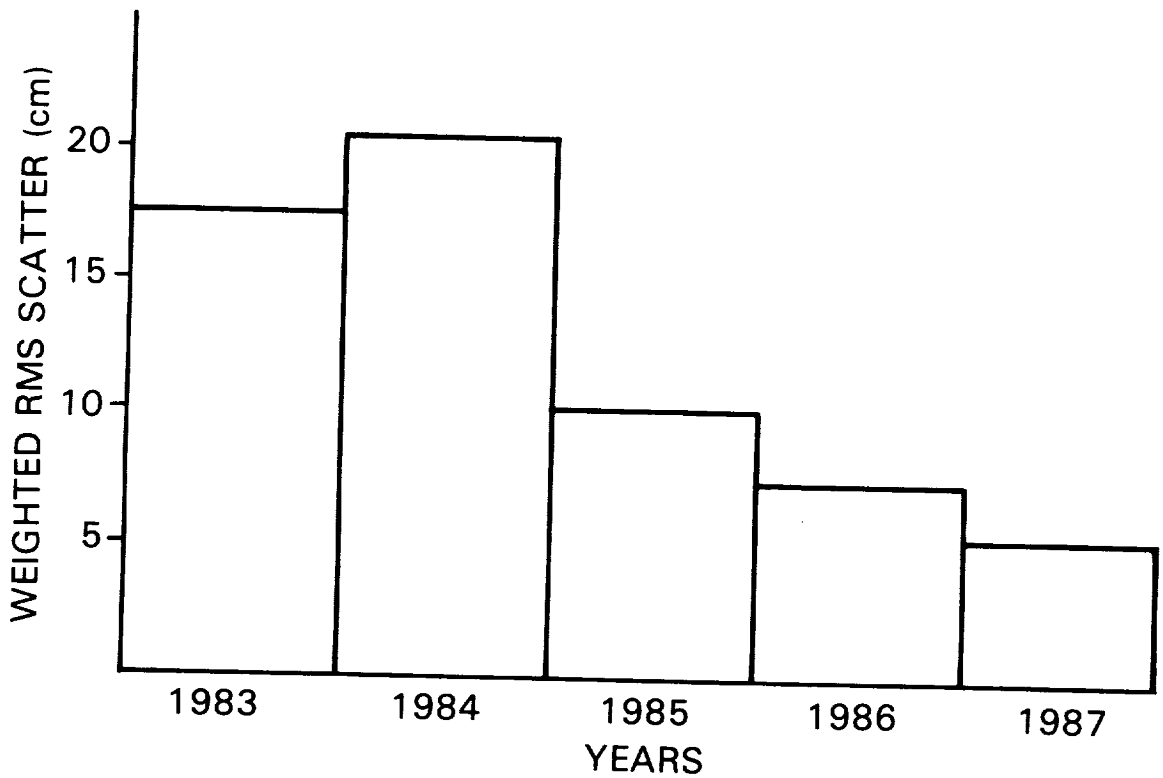

Figure III-5 Five-year improvement in LLR data quality.

Figure III-6 McDonald Laser Ranging Station (MLRS).

TABLE III-3

LLR SYSTEMS COMPARISON

	MLRS	HALEAKALA
Wavelength (nm)	532	532
Power Energy/Pulse (mj)	20-150	180
Pulse Repetition (pps)	10	5
Divergence (mrad)	0.01	0.01
Receiver Sensitivity (photon)	1	1
Pulse Width (psec)	200	200
Receiver Diameter (cm)	76	152
Range Accuracy (cm)	3-8	2-4

bring the images from all the lenses to a single detector.

Lageos-I ranging started in 1980 and collocation testing was conducted in 1981. Although a few lunar returns were received as early as 1977, significant lunar returns were not obtained until a major overhaul of the system was done by the University of Hawaii in early 1985. In February 1985, in one observation session the facility acquired more lunar returns than all previous LLR observations at that site. Since then, additional improvements have been made to get a stable telescope with good light efficiency. A pathlength corrector system was designed and fabricated to make the pathlengths for all lenses the same. In 1987, the lunar system was upgraded with the MCP tube and the Tennelec Discriminator. The performance achieved was 4 cm single-shot (rms), the best performance achieved to date by any LLR facility.

c. Orroral Valley Facility

The original LLR facility in Orroral Valley, Australia, was provided to the Survey Mapping Group of the Australian Survey Office (formerly National Mapping - Natmap) by NASA on an indefinite loan basis in 1974. This station was originally owned by the Air Force Geophysical Laboratory (AFGL) and located in Tucson, Arizona. It has a special 152 cm Cassegrain telescope that is used for both transmitting and receiving. In 1979, NASA and the Survey Mapping Group initiated discussions of a joint program for: (1) upgrading the LLR capability, and (2) expanding the capability to include SLR. In April 1982, a joint venture Agreement was formalized. Under this Agreement, the facility was to be modified to achieve a Lageos ranging precision of 1.5 cm and a LLR precision of 5 cm.

The Natmap Laser Ranging Station (NLRS) ranged to Lageos-I and the Moon in 1984; however, routine LLR has not yet been demonstrated. In 987, an Operations Readiness Review was held by the CDP in conjunction with the NASA LLR Management Operations Working Group. A series of test programs were established to seek the cause(s) for a low level of laser signal return.

4. Future Developments

Throughout the long history of the development of SLR systems, the principal limitations on systematic error reduction has cycled between system technology and accuracy of satellite ephemerides. The initial improvement in ranging precision from several meters to decimeters resulted from better gravity field models for orbit determination, more accurate timing systems, and improved analytical techniques. The advancement from decimeter to centimeter precision is mostly attributable to new system technologies. In 1983, the specialized Lageos-I (GEM-L2) gravity field model made possible a factor of two improvement in ranging precision. Finally, in 1986, the introduction of the MCP photomultiplier tube led to the demonstration of the first sub-centimeter (7 mm) single-shot ranging precision. Now incorporated into the Network, the MCP (along with other system changes) have produced systems with a single-shot precision of 7 mm. Thus, the goal, first established in 1969, of centimeter-level ranging precision has been met and exceeded.

The continued improvement in the accuracy of these space geodetic measurements has led to more significant results from the analysis and interpretation of these data and has been strongly supported by the Program's investigators. At the March 1987 meeting of the CDP Investigator Working Group, a new set of performance goals for geodetic

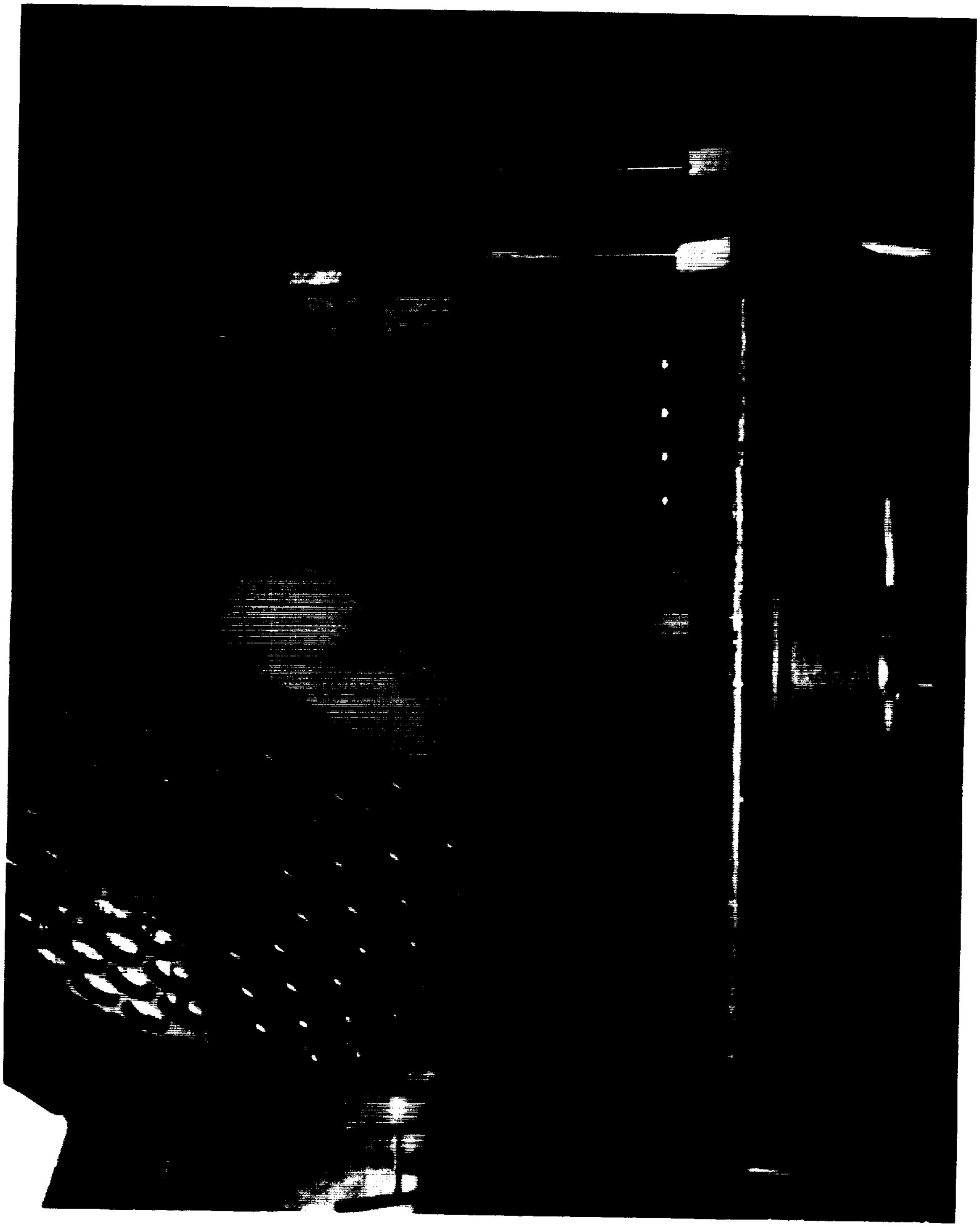

Figure III-7 Mt. Haleakala, Hawaii, Lunar Ranging Receiver Telescope.

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measurements was recommended. These are summarized as follows (Jordan and Minster, 1987):

- o To contribute to the improvement of existing models of present- day motions among the major plates, the tangential components of relative velocities on inter-plate baselines must be resolved to an accuracy < 3 mm/year.

- o Measuring the velocities between crustal blocks to 5 mm/year can place geologically useful constraints on the integrated deformation rates across continental plate-boundary zones such as the western U.S.

- o To detect the horizontal motions associated with the secular deformation of stable plate interiors, the tangential components on intraplate baselines must be resolved to an accuracy of < 1 mm/year.

From an instrument standpoint, these requirements for mm/year accuracy of velocity determinations translate to millimeter measurement accuracy. The velocity accuracy is heavily dependent on the systematic errors in the measurements. The current SLR systems with 7 mm single- shot (rms) would have sub-millimeter normal point (rms) precision, if there were no systematic errors. However, in 1987, all the SLR systems have uncalibrated systematic instrument errors of a magnitude from 2 mm (Moblas-7) to 10 mm (Moblas-4). The main thrust, in the near future, will be to implement the Moblas-7 calibration improvements in the rest of the NASA stations: this will reduce the systematics for these stations to the few millimeter level. Further improvements, such as more refined calibration methods, more accurate time interval units, and lower-jitter MCP detectors, will need to be developed to reach the submillimeter level.

After the reduction of the instrument systematic errors, the atmospheric propagation errors will become dominant. Presently, propagation corrections are computed from measurements of station temperature, pressure and humidity. Recent improvements in the formulas for these calculations have reduced this error to 5 mm, and further work is being conducted to see if additional error reduction may be possible. In parallel with this, research on two-color ranging is being conducted to develop a system that can directly measure the atmospheric propagation to the millimeter level.

The problems with highly mobile systems of the TLRS type appear to indicate that a limit has been reached in the mechanical miniaturization of SLR systems. Future systems will probably be more robust, but still retain many of the technological innovations introduced in TLRS-1 through -4. Several countries, including Japan and Italy, have expressed interest in and are proceeding with development of TLRS-type systems.

SLR and LLR systems are expected to continue to evolve. However, the next steps such as introduction of multi-color laser ranging or total system automation are expensive and will not be available as field capabilities for many years. Also, it is likely, considering the applications of GPS and the GLRS to geodynamical problems, that future ground-based laser systems will be designed as permanent or semi- permanent observatories.

B. VERY LONG BASELINE INTERFEROMETRY

The VLBI technique involves two or more radio antennas to receive microwave signals from extragalactic radio sources. The broad-band noise signal from the radio source being observed is received at each antenna and recorded with precise time information provided by the station atomic clock. The recorded signals are cross-correlated in pairs at a dedicated correlator facility to determine the difference in arrival time of the signal at the two ends of the baseline. This time delay is very sensitively dependent on the length and orientation of the baseline with respect to the reference frame defined by the set of extragalactic radio sources. Typically, a total of 100 to 200 observations are made on 10 to 14 radio sources during a 24-hour VLBI experiment. From the VLBI delays, geodetic and geophysical parameters can be estimated. The current formal precision of VLBI measurements is at the level of 1 cm for baseline length, 1 mas for the components of polar motion, and 0.05 ms for UT1 (see Clark et al., 1985).

Prior to the initial geodetic VLBI experiments in 1969, VLBI was used principally for radio astronomy. In the early 1970's, VLBI using microwave signals transmitted from the Apollo Lunar Science Experiment Packages (ALSEP) was used to study the rotation of the Moon and ALSEP coordinates. In the period from 1971 to 1978, radio astronomy telescopes at the Haystack Observatory in Westford, Massachusetts, the National Radio Astronomy Observatory (NRAO) in West Virginia, the Deep Space Network (DSN) Goldstone tracking facility in California, the Owens Valley Radio Observatory (OVRO) in California, and the Onsala Space Observatory of the Chalmers University of Technology in Onsala, Sweden, carried out extensive VLBI observing campaigns to study the application of VLBI to geodesy. These experiments used the Mark-I VLBI system which recorded on standard 7-track computer tape. During the same period, the DSN Stations in California, Spain, and Australia conducted VLBI experiments to determine the applicability of VLBI to deep space navigation and to monitor Earth orientation. These experiments used the Mark-II VLBI system based on video tape recorders.

In 1974, the baseline between the Haystack Observatory, Massachusetts, and Goldstone, California, was determined with a repeatability of 16 cm. By 1978, 4 cm repeatability was demonstrated on the baseline between Haystack and OVRO.

The Mark-III system developed jointly by NASA, NRAO, and Haystack for both geodesy and radio astronomy became operational in 1979 and is the standard CDP system now in use. The major advances over the earlier systems are: (1) much greater recorded bandwidth for enhanced sensitivity; (2) simultaneous dual-frequency observing to calibrate the ionosphere; (3) automated operation; (4) real-time measurement of meteorological parameters; and (5) receivers with 400 MHz bandwidth at X-band (8 GHz) and 80 Mhz at S-band (2 GHz).

VLBI has evolved into two distinct system configurations: (1) a fixed observatory permanently equipped with a large radio antenna (9-100 meter diameter), low-noise receiver, VLBI recording system, hydrogen maser time and frequency standard, and auxiliary instrumentation; and (2) a mobile VLBI station with a complete self-contained, self-supporting antenna (3-5 meter diameter) and electronics system which can be moved from one location to another (see Davidson and Trask, 1985).

1. Observatory VLBI

The stations used in the first two years of the CDP included Haystack, NRAO, OVRO, Onsala, the Harvard Radio Astronomy Station (HRAS) at Fort Davis, Texas, Chilbolton (England) and the Max Planck Institute for Radio Astronomy (MPIfR) in the FRG. In 1981, the Westford antenna at the Haystack Observatory was equipped as a dedicated geodetic VLBI station and the NASA Space Tracking and Data Acquisition Network (STDN) station in Mojave, California, was transferred to the CDP. The Mojave Station was planned as a base station for the mobile VLBI systems, and the implementation of VLBI at Mojave was completed in 1983. The Mojave Station (Figure III-8) was transferred to the NGS in March 1984 as part of the operational system for monitoring the National Crustal Motion Network (NCMN).

A dedicated VLBI Station constructed at Wettzell, FRG, jointly by the IfAG and the University of Bonn began regular operations in late 1983. The NGS Station at Richmond, Florida, also started operations at the end of 1983. These two stations, along with Westford, Massachusetts and the HRAS in Texas form the core of the POLARIS-/IRIS Network, which makes observations for 24 hours every five days to monitor polar motion and UT1. In addition, the Westford and Wettzell Stations are operated for one hour each day to measure UT1 with higher time resolution. Onsala, Sweden, participates in IRIS once per month. In 1987, the station of the University of Bologna at Medicina, Italy, joined the IRIS Network for occasional research experiments.

Development of a dedicated VLBI station at Kashima, Japan, was undertaken by the Radio Research Laboratory (RRL) of the Japanese Ministry of Communications in 1982 and completed in 1984. Initial observations were carried between Kashima and the Mojave, California, and Ft. Davis, Texas stations in early 1984 (Saburi et al., 1984). Later in 1984, Kashima participated with CDP-equipped stations in Fairbanks, Alaska (formerly belonging to NOAA - see Figure III-9); Kauai, Hawaii; and Kwajalein, Marshall Islands, in first-epoch VLBI measurements of the motion and stability of the Pacific Plate. These measurements have been repeated every year, except that the Kwajalein Station was not included in 1987. The frequency of measurements with Kashima has increased, and in 1987, in an arrangement with the NGS IRIS Project, RRL began monthly observations of polar motion and Earth rotation with the Fairbanks station. In 1986, the Shanghai Observatory of the Academia Sinica of China began Mark-III VLBI operations using a 6-meter diameter antenna. A completely new facility of the Shanghai Observatory with a 25-meter diameter antenna became operational in 1987 and participated in a trans-Pacific experiment with Kashima, Japan; Kauai, Hawaii; and Fairbanks, Alaska. Two other VLBI observatories are planned in China: one in the northwest (at Wulumuqi) and one in the south (at Kunming).

In 1986 the DSN began installing Mark-III VLBI recording systems at its three tracking facilities at Goldstone, California; Canberra, Australia; and Madrid, Spain.

The Very Long Baseline Array (VLBA) being constructed by the NRAO may have a significant impact on geodynamic research (Fomolant, 1987). It will consist of ten, 25-meter diameter, antennas across the U.S. between Hawaii and the Virgin Islands. The recorders will have a Mark-III-compatible mode. S-band and X-band receiving capability is planned so that the Array will be able to link with existing geodetic VLBI stations. Calibration periods on a weekly to daily basis of up to 10-20% of the available observing time will provide geodetic information about the geometry of the Array and the orientation of the Earth.

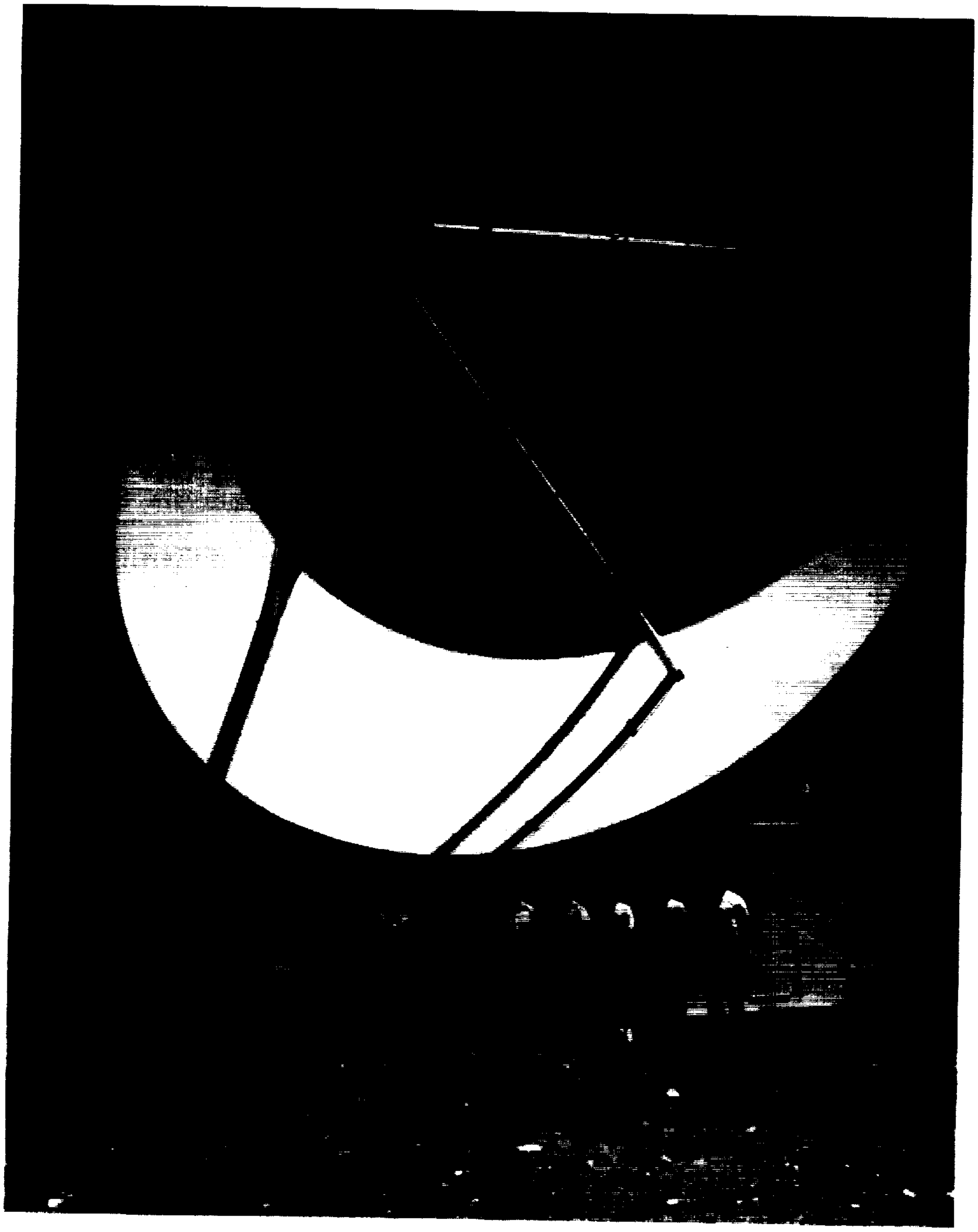

Figure III-8 Mojave, California, VLBI station.

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Figure III-9 Fairbanks, Alaska, VLBI station.

A second dedicated VLBI station in Italy is under construction by the Piano Spaziale Nazionale at Matera and should be operational by 1988. A third Italian VLBI station is planned for Sicily. Saudi Arabia plans to have a VLBI station by 1989. Since 1979, nineteen radio antennas have been equipped by the U.S. and other countries with Mark-III (or compatible) systems.

The wide geographic distributions of the fixed VLBI stations and the requirement of simultaneous observations of the same radio source makes it impossible to use a single worldwide network. Observing campaigns therefore use a smaller set of stations to measure particular crustal dynamics phenomena. The primary Networks are Atlantic (European and North American Stations), Pacific (in and around the Pacific Basin), North American (stations in Conus, Alaska, and Canada), and polar (Kashima, Japan; Fairbanks, Alaska; Westford, Massachusetts; Onsala, Sweden; and Wettzell, FRG). Each type of CDP observing campaign is conducted two or more times each year.

2. Mobile VLBI

The first mobile VLBI system, MV-1 (Figure III-10), was initiated in 1973 using a 9-meter erectable antenna, but this system required a week for assembly at a new site. To improve system mobility, work was started in 1978 on a 4-meter VLBI mobile station, MV-2 (Figure III-11). This station was expected to reduce site transition time to one day. Procurement of the first mobile VLBI unit specifically designed for field operations, MV-3 (Figure III-12), was initiated in 1980. This system became operational in 1983. Each mobile station consists of a transportable antenna with a dismountable receiver and a separate electronics trailer containing the Mark-III recording system and hydrogen maser.

In 1981, MV-1 and MV-2 could observe at only X-band. However, they occupied a total of 14 sites and operated in conjunction with base stations at OVRO, Goldstone, and HRAS. The larger antenna at the base stations provided the collecting area to overcome the lack of sensitivity of the smaller mobile antennas. During 1982 and 1983, and between measurement campaigns, MV-1 and MV-2 underwent several upgrades. The MV-1 electronics van was reworked and, in 1983, MV-1 was permanently located at Vandenberg Air Force Base in California. The MV-2 antenna was fitted with a dichroic reflector plate to provide dual S-X band capability.

Based on an interagency plan for operational geodynamics and geodetic services (ICCG, 1981), an Agreement was concluded between NASA and NGS in 1983 for the transfer of VLBI equipment. Under this Agreement, NASA transferred operational responsibility to NGS for mobile VLBI measurements in support of the CDP and the NCMN. This involved the transfer of the three MV's and the Mojave Station. MV-3 and the Mojave Station were transferred in March 1984. MV-1 and MV-2 were transferred in early 1985 after MV-2 was upgraded with a more efficient dual frequency focal point antenna feed.

Regional deformation measurements in California and the western U.S. by mobile VLBI systems and base stations increased from 32 baselines measured in 1982 to 144 measured in 1986. Reoccupation of sites in the San Francisco area, extensive southern California observations and intercomparison measurements of the SLR SAFE baseline were carried out using MV-2 and MV-3. Many of the measurements were repeated each year through 1987, some with an increased number of occupations per year. Several of

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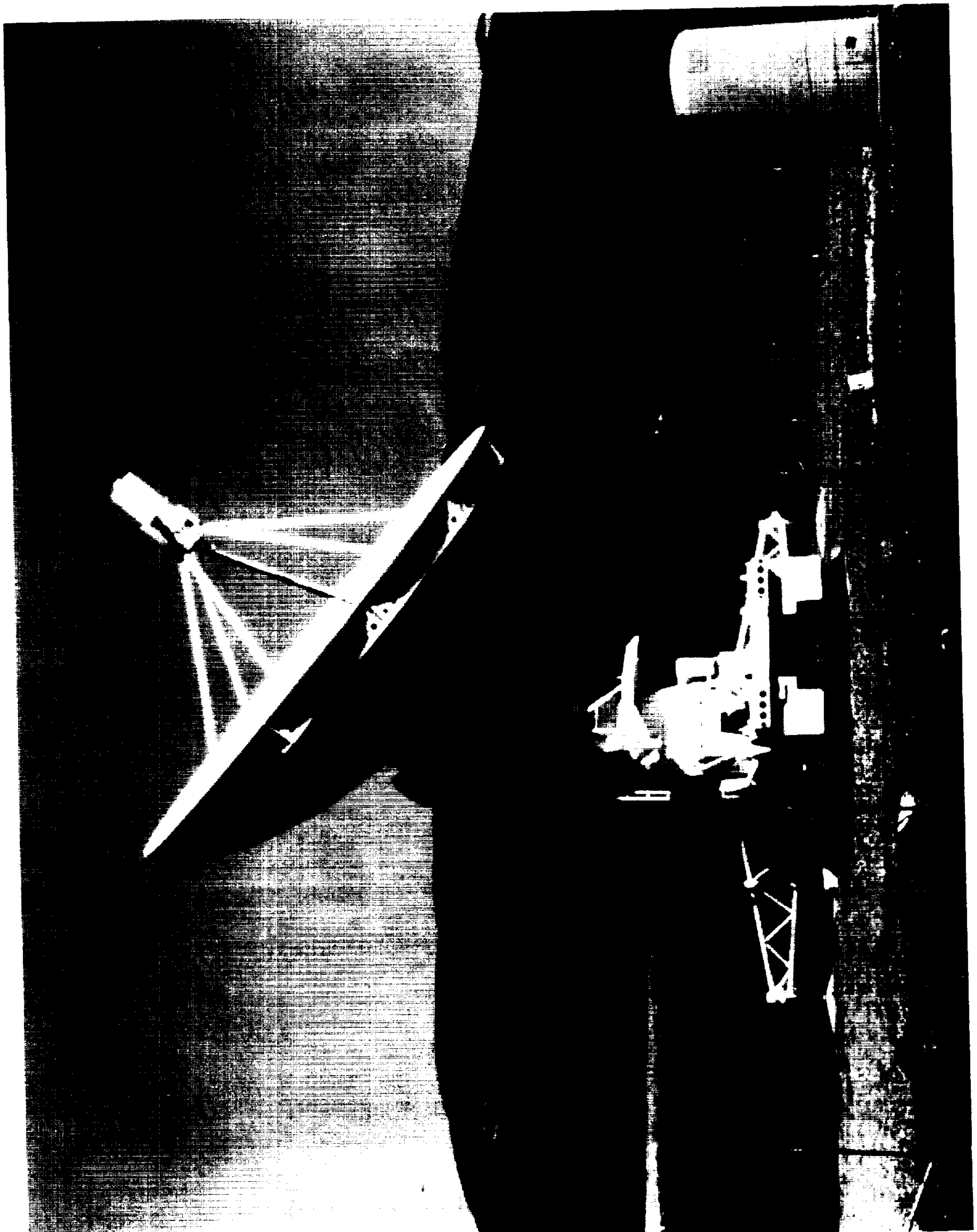

Figure III-10 Mobile VLBI station (MV-1).

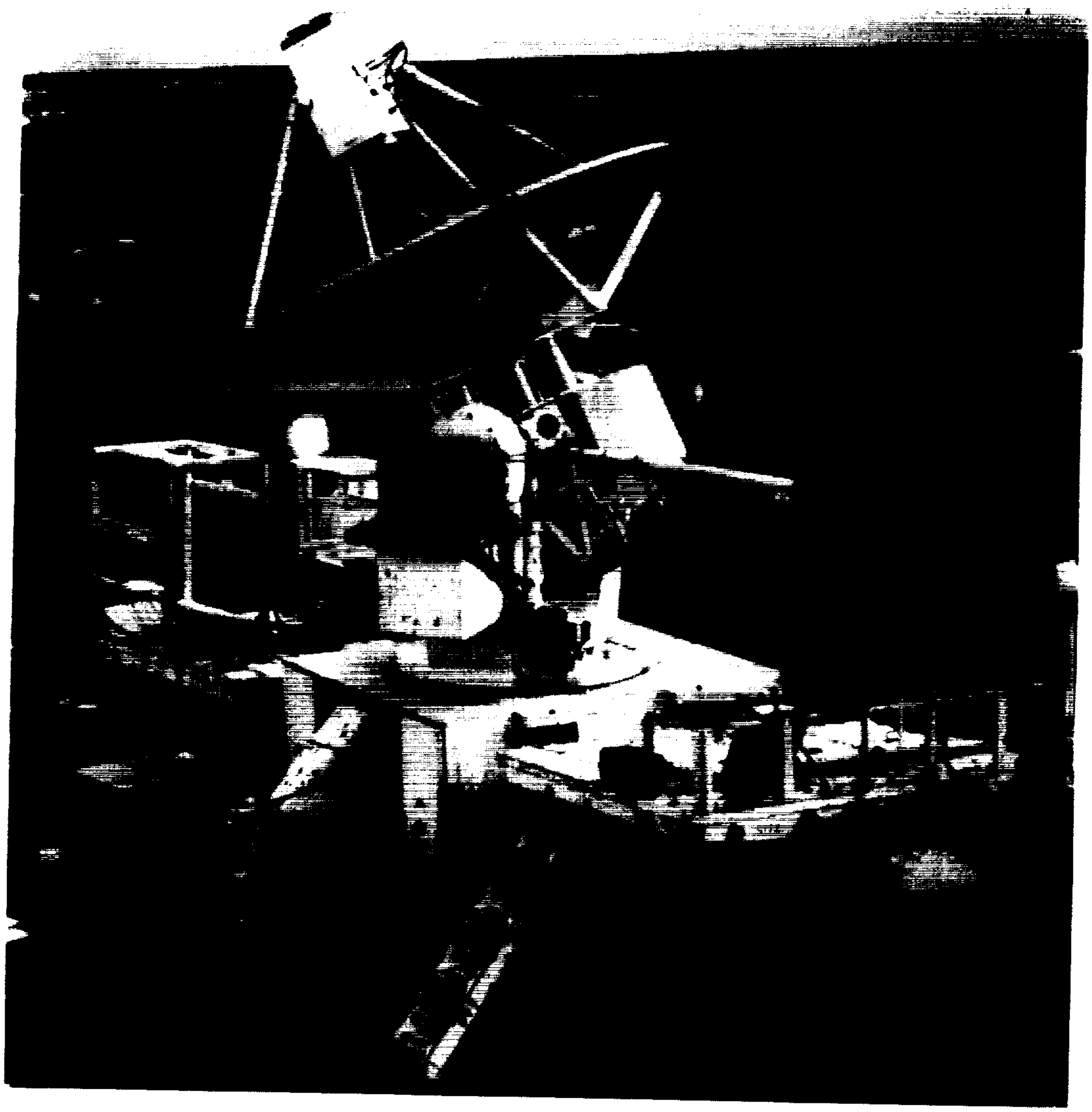

Figure III-11 Mobile VLBI station (MV-2).

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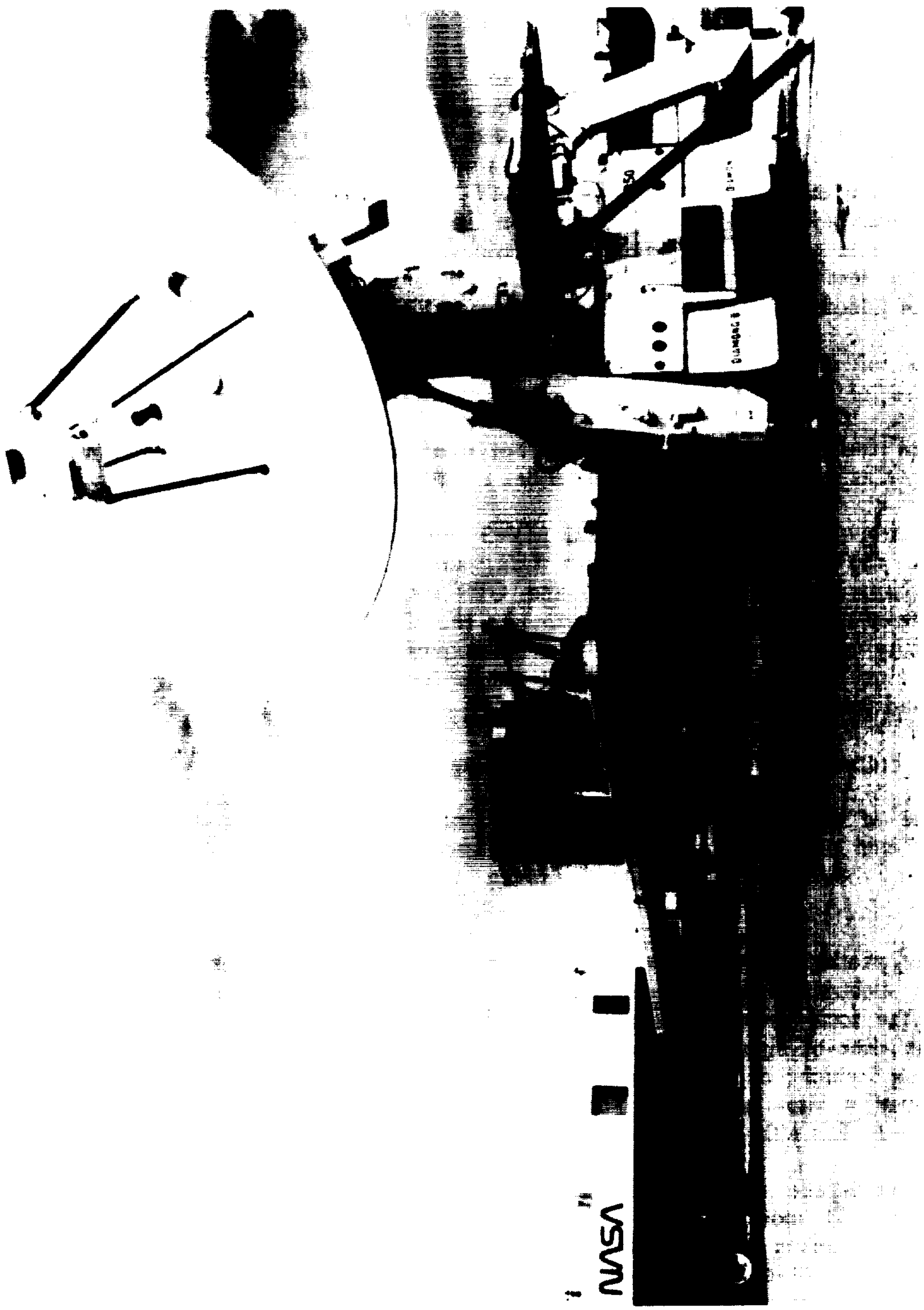

Figure III-12 Mobile VLBI station (MV-3).

the mobile VLBI sites in California have been visited more than a dozen times so that it is possible now to put realistic bounds on models of crustal strain around the San Andreas Fault.

Beginning in the summer of 1984 and repeated in 1985, MV-2 and MV-3 were transported to Alaska and visited eight sites in Alaska and Canada as part of the western North American regional deformation and plate stability studies. Fairbanks, Alaska, and Vandenberg, California, were the base stations. In 1986, only the Alaskan site measurements were made; and in 1987, only MV-2 was sent to visit a restricted number of sites. The primary reason for the reduction in measurements was the high cost of visiting such remote areas. During several sessions, measurements were also made by NGS using GPS to test the accuracy of the satellite technique, but the results so far have not been of adequate quality to replace or augment VLBI.

Part of the purpose for transfer of the mobile VLBI stations to NGS was to facilitate the use of VLBI by other Agencies, on a reimbursable basis, for operational geodetic services. The first example of this occurred in 1987, with NGS using MV-3 to visit four sites of the NCMN (sites which are not part of the CDP) and to obtain measurements in Bermuda as part of the NOAA Global Sea Level Program.

It is expected that MV-2 and MV-3 will continue to be used for studies of crustal motion in California, the western U.S., and Alaska for several more years. Extensive intercomparison of mobile VLBI and GPS measurements of baselines from 200 to 1,000 km are planned during this period. As the GPS technique matures and its accuracy and reliability can be assessed, the two techniques will become complementary. The mobile VLBI sites will become the fiducial marks for a denser, more extensive network of sites surveyed frequently using GPS.

3. Tropospheric Calibrations and Modeling

One of the major limitations of the inherent accuracy of VLBI is the calibration of the effects of the neutral atmosphere (Resch et al., 1984). These errors can be divided between the "dry" atmosphere (nitrogen and oxygen) and the "wet" atmosphere (water vapor).

The propagation delay at zenith caused by the dry component is typically two meters excess electrical path length. The correction at zenith can be accurately computed using the local pressure as a measure of the amount of atmosphere overhead. The delay in the line-of-sight of the VLBI observations must be calculated from a mapping function which depends on the actual structure of the atmosphere. Davis (1986) developed a site- and season-dependent model based on ray tracing of extensive sets of radiosonde data although, in practice, a single universal set of coefficients is used.

Although the excess path from water vapor is rarely greater than 25 cm at zenith, the effect is more difficult to model because meteorological parameters measured near the ground often do not correlate with the distribution of water vapor higher in the atmosphere. Studies indicated that a 2-3 cm error in estimation of the water vapor delay leads to errors in the vertical component of station coordinates of up to 10 cm.

A remote sensing technique was developed to measure the water vapor along the line-of-sight of the radio telescope using microwave radiometers. The Water Vapor Radiometer (WVR) operates near the 22.2 GHz resonant absorption line of water to sense the water content, and at other frequencies to separate the effects of water droplets and to calibrate the systems. Prior to 1981, seven WVR's were built by JPL but did not produce sufficient data to evaluate the technique. In 1983, after a detailed review, the CDP decided to redesign and refurbish four of the existing units. The work on the first WVR was completed in 1985. Current data indicate that the line-of-sight contribution of water vapor can be measured with a precision of 2-3 mm. A WVR has been operating for a long period at the Mojave Station. Application of the WVR data to a selection of Mojave VLBI data decreases the scatter of the vertical component of the station position while not affecting the scatter of the horizontal components.

Based on recommendations of the CDP review, JPL designed a new "J-Series" WVR (Figure III-13). The first model was completed in early 1985 and construction of a second unit was completed in 1986. A comparison of the new and retrofitted WVR's demonstrated a level of agreement between instruments at a few millimeters in zenith. The new design is considerably more compact and portable and appears to be more reliable than the older units (Janssen, 1985).

Another approach is to model the effects of tropospheric delays stochastically using a Kalman filter. This technique relies on the observed geometry and a knowledge of the statistics of tropospheric fluctuations to separate the tropospheric effect on each observation from other effects. Davis (1986) has shown that the non-dry tropospheric delay recovered by the Kalman filter can have temporal signatures very similar to the delay measured by a WVR operating at the same time.

4. VLBI Correlator Facilities

A dedicated VLBI correlator consists of two or more tape drives, special electronics for fast cross-correlation, a control computer, and software for detecting the interferometric fringes and generating the VLBI delays.

The first dedicated VLBI correlator was built for the Mark-1 system in the early 1970's at the Haystack Observatory and continued in use until 1978. The Mark-III correlator now used to process the bulk of CDP data was built by Haystack in 1979: a similar facility exists at MPIfR in Bonn, FRG. A Mark-III compatible correlator was developed by RRL and began operations in 1983.

In 1983, NOAA, USNO, NASA, and NRL concluded an interagency agreement for the development and operation of a correlator to be located at the USNO in Washington DC. The costs of the correlator and the operation were to be shared in proportion to Agency use. This "Washington Correlator" became operational in early 1986 and has been essentially devoted to processing data from IRIS and other NGS activities. Based on current workload projections, both the Washington and Haystack Correlators will be needed to process all of the VLBI data the Agencies expect to acquire over the next several years.

5. Technical Developments

Over the past five years the precision and efficiency of VLBI measurements have been improved through hardware and analytical modeling changes. The baseline repeatability for lengths of 245 km to 5600 km are listed in Table III-4.

A cryogenic Field Effect Transistor (FET) was developed for the CDP receivers and

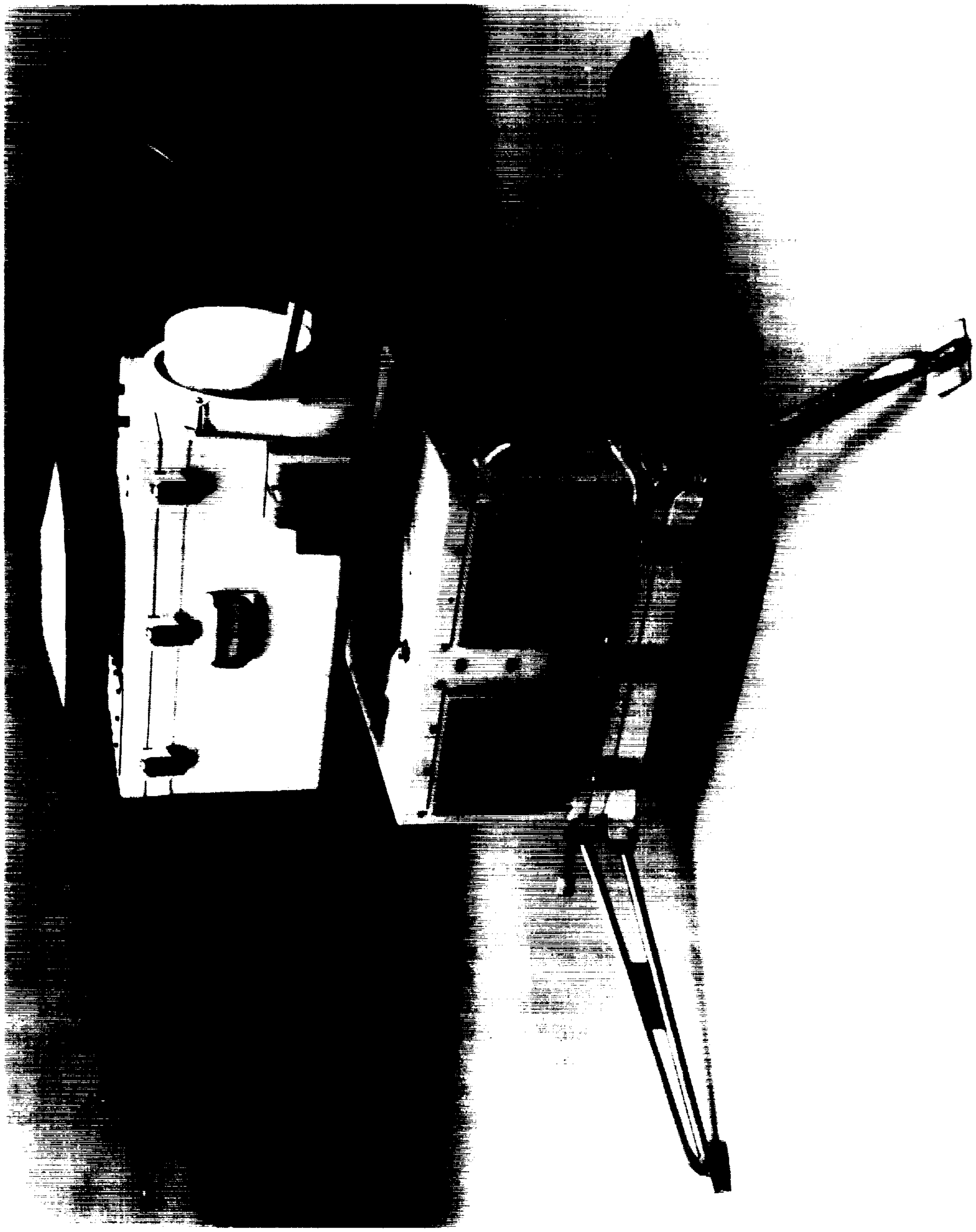

Figure III-13 J-series Water Vapor Radiometer instrument.

C-2

TABLE III-4

DEMONSTRATED VLBI BASELINE REPEATIBILITY

Baseline	Length km	RMS REPEATIBILITY Length mm	Transverse mm
Mojave - OVRO	245	7	6
Mojave - Monument Peak	271	9	8
Mojave - Vandenberg	351	11	12
Onsala - Wettzell	920	5	-
OVRO - Ft. Davis	1508	.9	8
Mojave - Westford	3904	8	-
Haystack - Onsala	5600	15	-

installed on all U.S. fixed and mobile antennas and at many international observatories. More recently, a new High Electron Mobility Transistor (HEMT) has been tested which improves X-band performance by 20-30° K, and S-band performance by 8-10° K. HEMT's have been installed at the Mojave, Hat Creek, and Fairbanks Stations and will be installed at the other CDP stations.

A high density tape head modification was developed and implemented at a number of stations and at the correlators. By narrowing the tracks and recording multiple offset passes on the tape, the modification increases the tape density by a factor of twelve. Typical tape usage is reduced from 35 tapes to three tapes per station per day, with a significant savings in cost and logistics.

The MV-2 was upgraded by replacing the original antenna with a 3.05-meter satellite TV antenna and by installing a high-performance dual frequency focal point feed. The antenna is constructed of four sections that can be easily mounted and removed manually. With the antenna dismantled, the former road travel restrictions imposed on the previous wide-load trailer are removed. The dish surface is a considerable improvement over the original and, because of the low cost, the entire dish can be replaced when the performance is degraded by use.

Improvements in the CDP VLBI analytical models and software have been made. The program CALC used by the CDP and NGS to compute theoretical delays was modified to use the J2000.0 reference frame, IAU 1980 nutation, ocean loading, and the pole tide. The analysis system was extended through an interface called GLOBL to handle an indefinitely large number of data sets using a sequential least squares estimator. Solutions incorporating over 200,000 points including both fixed and mobile data have been generated.

The analytical software also has been extended to apply Kalman filtering to stochastic processes such as the station frequency standards and the troposphere. Filtering provides a more realistic model of these processes at the current, much-improved accuracy of the systems. Studies of various effects on hydrogen maser frequency standards and the resultant propagation of errors into VLBI measurements show that improved analytic parameterization of the clocks improves the recovery of geodetic parameters. It was also found that with good environmental control of the masers, systematic errors are significantly reduced, and post-fit residuals for the entire VLBI system are similar in behavior to laboratory measurements of the masers themselves.

A recently updated error analysis for VLBI for baseline lengths of 400 km and 4000 km, Tables III-5a and -5b, indicates that the transmission media and unmodeled systematic errors are the chief remaining contributors.

Having reached the goal of a few centimeter precision for extended baselines, new goals have been established for VLBI. These goals, which are consistent with the velocity accuracy requirements defined by the CDP investigators, have been defined as follows:

a. To achieve subcentimeter precisions for baseline measurements;

b. To substantially improve the precision of vertical measurements;

c. To produce UT1 data with precisions of 0.01 ms;

Table III-5(a)

1987 VLBI ERROR BUDGET ESTIMATES

400 Km Baseline Length

Error Source	Kalman Filter			WVR		
	Vertical	Transverse	Length	Vertical	Transverse	Length
Uncalibrated Instrumental Bias	6	4	4	6	4	4
Antenna Structural Deformation	6	2	2	6	2	2
Uncalibrated Ionospheric Biases	2	1	1	2	1	1
"Dry" Tropospheric Biases	3	2	2	3	2	2
"Wet" Tropospheric Biases	30	2	2	15	2	2
UT1 + Polar Motion Mapping	2.5	2.5	zero	2.5	2.5	zero
Unmodelled Source Structure	3	3	3	3	3	3
Analyst "Style" Biases	6	4	4	6	4	4
R.S.S. Total Error Estimate	32 mm	8 mm	7 mm	19 mm	8 mm	7 mm

Table III-5(b)

1987 VLBI ERROR BUDGET ESTIMATES

4000 Km Baseline Length

Error Source	Kalman Filter			WVR		
	Vertical	Transverse	Length	Vertical	Transverse	Length
Uncalibrated Instrumental Bias	6	4	5	6	4	5
Antenna Structural Deformation	6	2	2	6	2	2
Uncalibrated Ionospheric Biases	2	1	2	2	1	2
"Dry" Tropospheric Biases	3	2	3	3	2	2
"Wet" Tropospheric Biases	30	2	10	15	2	6
UT1 + Polar Motion Mapping	25	25	zero	25	25	zero
Unmodelled Source Structure	3	3	3	3	3	3
Analyst "Style" Biases	6	4	4	6	4	4
R.S.S. Total Error Estimate	41 mm	26 mm	13 mm	31 mm	26 mm	10 mm

d. To produce polar motion data with precisions of 0.2 mas.

C. GLOBAL POSITIONING SYSTEM

1. Background

The advent of low-cost portable receivers for highly accurate measurement of baselines using GPS is ushering in a new era of geodesy. A number of important geological and geophysical questions can be addressed with this measurement capability which could not have been answered before with VLBI or SLR techniques. This is due to the larger number of observations which can be made economically with a GPS-based system, with the consequent potential for rapid measurements of the spatial and temporal variations of crustal strain.

The goals of the NASA GPS program are: (1) to develop a GPS-based geodetic system capable of subcentimeter accuracies over baselines up to continental length; (2) to demonstrate the accuracy of this developing system by a series of field measurement campaigns in key tectonic regions; and (3) to support related scientific investigations. An additional goal is to support active participation in GPS-based geodetic programs by Federal Agencies, international scientific groups and universities.

Over the past several years, major advances have been made in the understanding of the performance of GPS-based systems and their limiting error sources. The fiducial point concept, in which GPS terminals are fixed and collocated at a network of well-distributed VLBI or SLR sites, is essential to high accuracy relative positioning. During a campaign, these fixed terminals and a number of mobile terminals concurrently observe the constellation of visible GPS satellites: the fiducial observations serve to control the ephemerides of the satellites through the a priori site coordinate information provided by prior VLBI and SLR measurements. With the POLARIS network, regional baseline precisions of 0.005-0.03 ppm have been demonstrated for one horizontal component. The accuracy of the GPS system, expressed in terms of the level of agreement with independent VLBI measurements, is currently in the range of 1-2 cm horizontal and 3 cm vertical for 250 km baselines.

The key technology elements which are limiting current accuracy have been identified, and the effect of improvements in these elements on future system performance have been assessed. These elements include: limitations in current GPS receiver capability; the effects of multipath at the ground site and possibly also at the GPS satellite array; geometrical limitations of the present GPS constellation; use of water vapor radiometers; the accuracy with which the fiducial point locations are maintained; the distribution of fiducial points; and the accuracy of the modeling of the GPS satellite orbital dynamics. These studies have aided in the definition of a five-year technology development program that should yield system accuracies of better than one centimeter for baselines up to 3000 km and 0.003 ppm accuracies for longer baselines.

2. Technology Development

Three major development activities have been underway: GPS system modeling and software development; GPS receiver design and development; and development and demonstration of a second-generation water vapor radiometer.

Improved stochastic models for the clock processes, the tropospheric delay, and the ionosphere are leading to significant improvements in repeatability of baseline and ephemeris results. The use of GPS ephemerides derived from multi-day fits has greatly improved the repeatability of the baseline results. Figure III-14 illustrates current repeatability for a baseline measured in November 1985 and spanning the Gulf of California.

The software development has benefited from a large heritage of models and algorithms from VLBI systems and from planetary navigation programs developed earlier. The Orbiter Analysis and Simulation Software (OASIS) system provides a next generation simulation and covariance analysis capability. Complete documentation of this software package is available. The GPS Inferred Position System (GIPSY) is a complete data analysis and data management system required for centimeter-accuracy geodesy and GPS ephemeris generation. Testing and shakedown of the GIPSY software, which ultimately relies on repeatability and comparison with collocated VLBI, has led to an operational system for the processing of GPS data. Copies of GIPSY are being used now by other research groups within the U.S.

Intercomparisons of the performance of current generation GPS receivers have identified key functional characteristics requiring improvement. The next generation GPS receiver should be capable of simultaneous (without multiplexing) dual-band carrier phase observations of all visible satellites without cycle dropouts and should achieve subdecimeter ranging accuracy. It should be adaptable to high dynamic environments and its antenna/backplane assembly should be optimized against multipath. With these objectives in mind, an advanced receiver design effort began at JPL in 1984 with a definitive development plan completed in 1985. This receiver is called the "Rogue"; it is all-digital from the IF stage and makes extensive use of VLSI gate array technology. The first prototype pair of receivers began tests in 1987. The 50-meter baseline tests have yielded millimeter agreement with ground truth using the carrier phase measurements, and 1-2 cm agreement using the P-code pseudorange. Figure III-15 shows approximately 20 cm range residuals for a single Rogue receiver observing a single GPS satellite. This particular linear combination of pseudorange and carrier phase measurements is dominated principally by P-code multipath errors but the range and ionospheric effects have been removed. The prototype receivers will undergo further field tests through early 1988.

3. System Tests and Field Experiments

The NASA GPS program has had three major system tests building on the prior NOAA-coordinated interagency test of early 1984 (Goad et al., 1985). A week-long test in March 1985 involved 19 different organizations and a total of 14 GPS receivers located at fiducial sites in North America and at key sites in California, most of which include VLBI facilities. A major objective of this test was the intercomparison of baselines recovered using GPS with those obtained by VLBI. Most future experiments, including those conducted in the Caribbean, will include these California sites as benchmarks to monitor performance as improvements and changes are made to the system configuration.

The November 1985 test included an additional three sites in the southern region of the Gulf of California, two of which were the SLR sites at Cabo San Lucas and Mazatlan, Mexico. The Mexican sites included WVR's. The analysis of these data has yielded information on the utility of WVR's in humid climates and will provide an

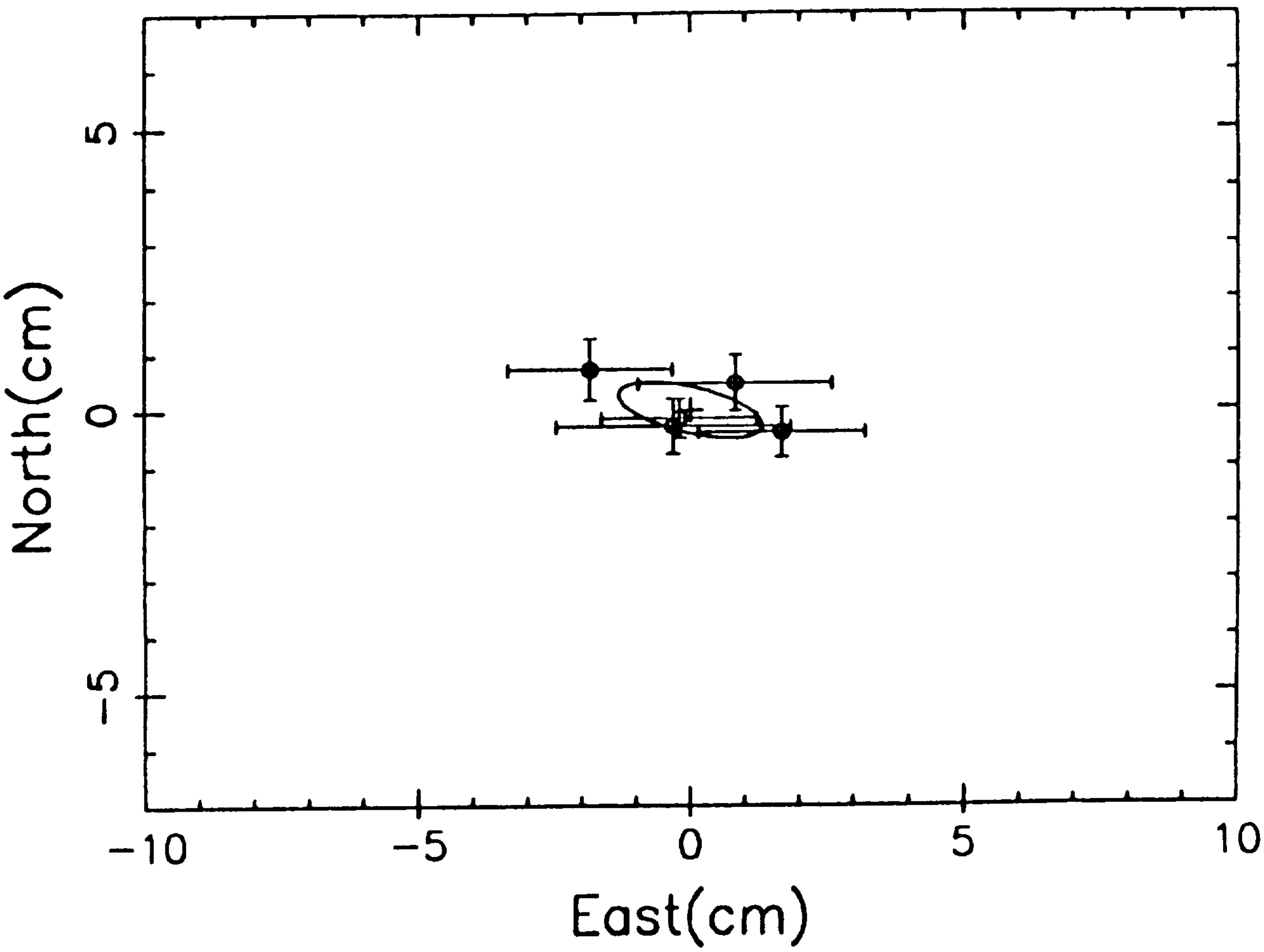

Figure III-14 Repeatability for a baseline measured in November 1985 and spanning the Gulf of California (Loreto-Mazatlan, 650 km).

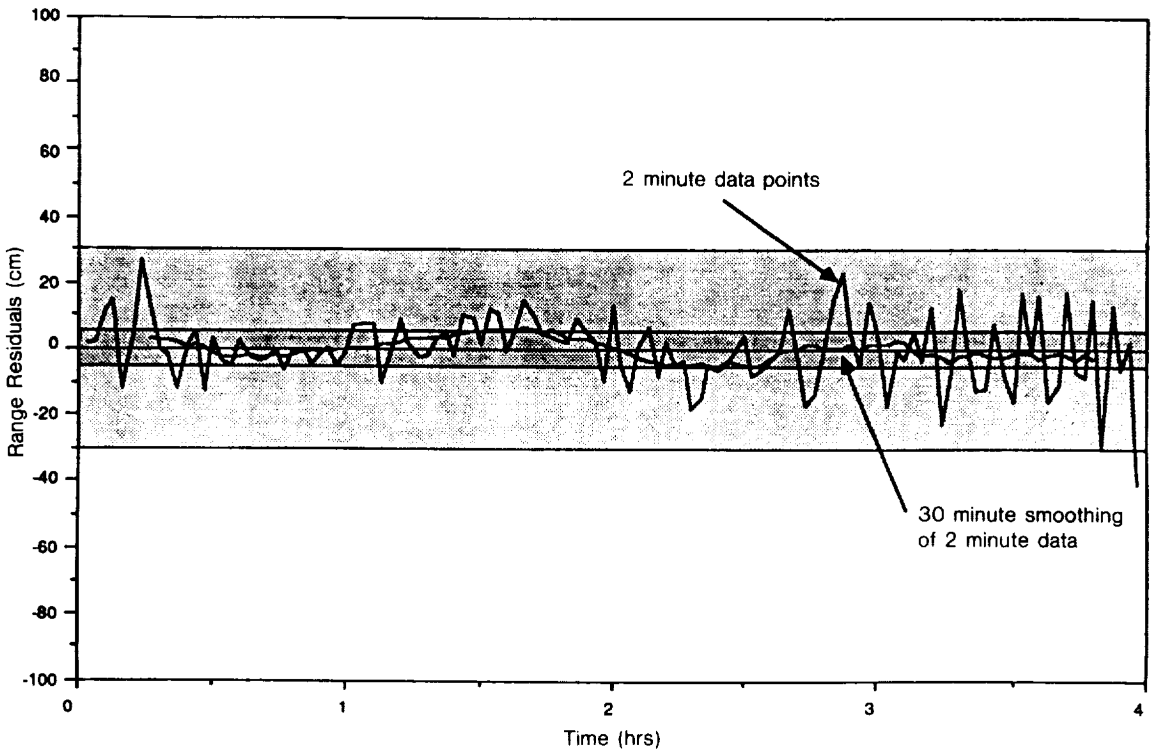

Figure III-15 Range residuals for a single Rogue receiver observing a single GPS satellite.

intercomparison of the GPS and SLR-derived baseline across the Gulf. The WVR data show that the water vapor content at both sites was high, but very uniform. Although use of WVR-based calibrations tends to give superior results to alternative stochastic modeling approaches, further tests in a variety of atmospheric conditions will be required to fully assess WVR utility.

The first GPS experiment in the Caribbean took place during June 1986 and involved five sites spanning the northern Caribbean plate boundary plus four fiducial sites. Shortly after, about two dozen sites in Southern California were occupied. Data analysis from these experiments is scheduled for completion in early 1988.

Results from the earlier campaigns appear to largely corroborate predictions made for current system performance. Data analyzed for the OVRO/Mojave 245-km baseline show repeatability in the north component of 1 cm, in the east component of 2 cm, and in the vertical 3 cm. Agreement in length with VLBI is at the level of 4 cm, but this also includes possible survey errors in tying together the two systems. These results were obtained using an adjusted wet tropospheric model and without use of WVR's at the fiducial sites. However, the conditions in California during the test were cold and hence very dry. Future tests to be conducted on a regular basis, in collaboration with the USGS, will address the specific question of the utility of WVR's for several hundred kilometer-length baselines in California.

4. Future Development

In early 1988, a second major Caribbean campaign was carried out; this included measurements in the northern Andes and across the western boundary of the Caribbean Plate to the Cocos Plate (See Figure III-16). The first measurements with the next generation GPS receiver and the new WVR instruments took place. Extensive multipath suppression studies are underway to achieve subdecimeter accuracy with the P-code pseudorange in controlled environments. The combined use of pseudorange with this accuracy and carrier phase measurements yields very accurate baseline and ephemeris results. In 1988, the first use of fiducial points that are more evenly distributed globally should yield submeter accuracies for the GPS ephemerides.

D. SPACE MISSIONS AND INSTRUMENTATION

1. Laser Geodynamics Satellite

For the past ten years, laser systems of many countries have ranged to, and received returns from, one of the simplest and cheapest satellites ever launched: Lageos-I. Today, its orbit is by far the best known of any satellite; the orbital position can be predicted to better than a meter a full year in the future, and the radial height can be determined to better than a decimeter. This single satellite has contributed to the determination of more information about the solid Earth than all the satellites of the previous twenty-five years.

Lageos-I is a 60-cm spherical mass of about 407 kg, with 426 uncoated cube corner retroreflectors imbedded in its surface. It was conceived as a dedicated reference for SLR, and was launched in May 1976 into a nominal 6000 km circular orbit (perigee 5858 km; apogee 5958 km; eccentricity 0.004) with an inclination of 109.8°. The high orbit was chosen primarily to maximize lifetime, which was initially estimated at several

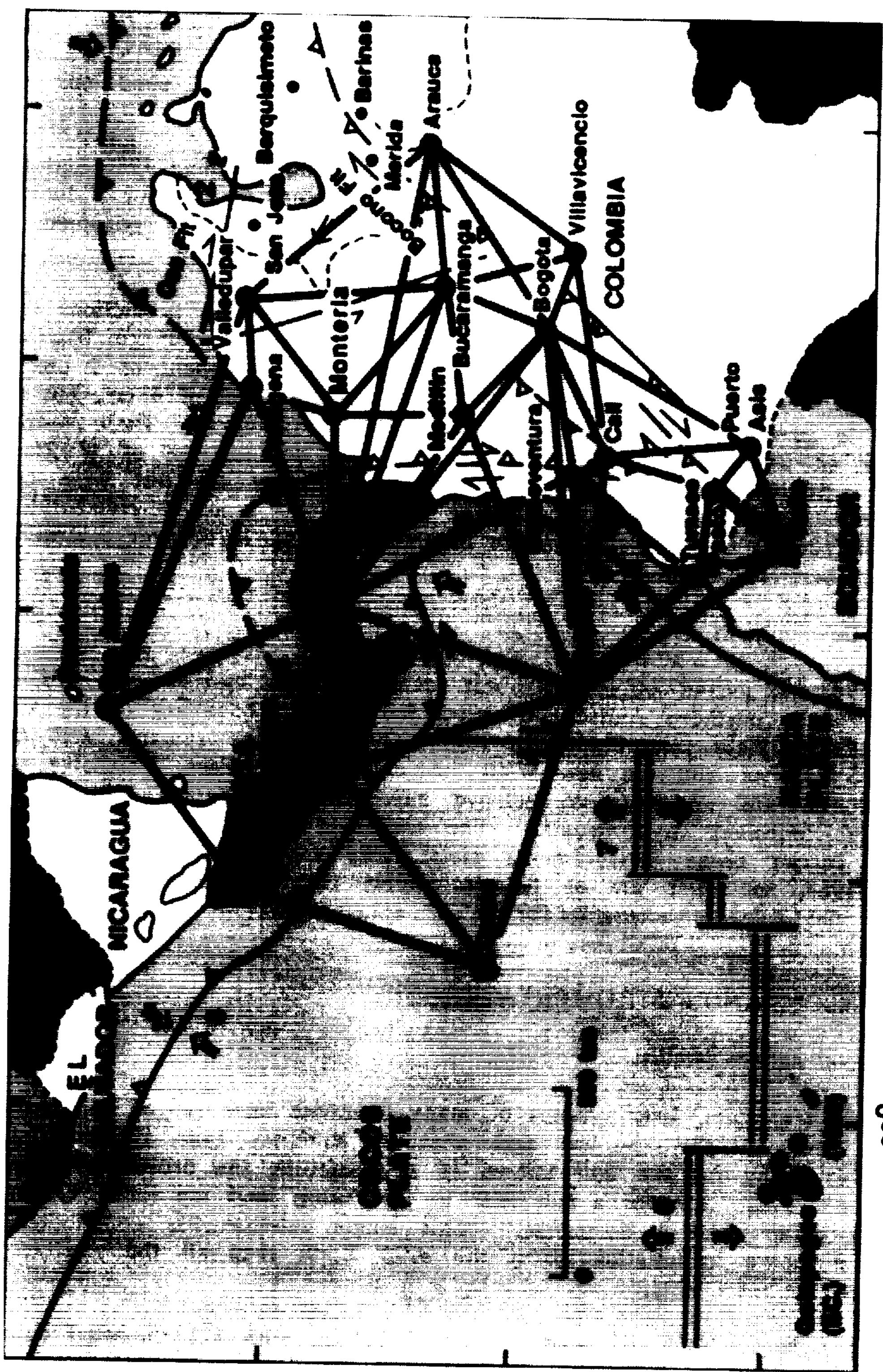

Figure III-16 GPS geodetic network planned for 1987-1989.

million years.

Prior to launch, laboratory tests of the far field illumination of the retroreflectors indicated a reduced return signal strength believed to be due to the cube corner dihedral angle. While it was known that ranging by existing SLR systems would be marginal for these conditions, it was decided that anticipated SLR system improvements would, in one to two years, overcome the Lageos-I deficiencies. Hence, an initial two-year period, defined as Phase I, was established for evaluation of the Lageos-I/SLR system performance. Phase II began with the selection of investigations proposed in response to a Lageos-I Announcement of Opportunity issued in 1978. Twenty-six investigations were selected. The results of these investigations were reported in a special issue of the Journal of Geophysical Research (JGR, 1985b).

With the initiation of the CDP in late 1979, the Lageos-I investigations were merged into the Project. Phase III of the Lageos-I mission began with the issuance of the CDP Announcement of Opportunity in 1982.

Shortly after the launch of Lageos-I, an unexpected continuous orbital acceleration was detected, evidenced as a decrease in the semi-major axis of approximately one millimeter per day. Studies of various potential sources for the acceleration, including errors in the magnitude of solar radiation effects, atmospheric drag due to He^{+}, charged particle drag, variable Earth albedo, etc., have not produced an acceptable explanation (Anselmo et al., 1983; Rubincam, 1985).

In 1984, as part of a cooperative program in Geodynamics between the Italian PSN and NASA, an agreement was signed for the development and launch of Lageos-II. Under this agreement, the PSN will build a spacecraft, essentially identical to Lageos-I, and provide both an orbital insertion stage (Italian Research Interim Stage - IRIS) and a Lageos Apogee Stage. NASA will conduct the Lageos-II optical ground tests, launch Lageos-II on the Space Shuttle, and track the satellite. The orbit of Lageos-II is planned to be identical to that of Lageos-I, except that the inclination will be 51^{o}. The Lageos-II launch was planned for late 1988, but has been delayed until the early 1990's because of the Challenger disaster.

A joint NASA/PSN Lageos-II Study Team concluded in a report issued in early 1983 (NASA/PSN, 1983b) that the combined Lageos-I and -II missions would: (1) improve the accuracy of baseline measurements by a factor of two; (2) increase the accuracy of polar motion data by 20%; and (3) contribute to better determination of unique terms defining solid Earth and ocean tides.

In 1985, it was suggested that stability of Lageos orbits and precise laser tracking could be used to test General Theory of Relativity by detecting the Lense-Thirring precession of the nodal lines of an orbiting satellite. However, to use Lageos-II for this purpose would have required modifying the orbit of Lageos-II to be perpendicular (76^{o} instead of 51^{o}) to that of Lageos-I to within 0.13^{o} and the difference in eccentricity to be less than 0.04. This change was investigated by the Lageos-II Science Working Group. Because of limitations of the IRIS stage and the desirability of maximizing Lageos-II coverage over the Mediterranean, the Working Group recommended retaining the 51^{o} orbital inclination. The strong interest in the Lense-Thirring relativity experiment has prompted consideration of a third Lageos mission specifically designed for this purpose.

Both the 1983 Airlie House Geodynamics Conference (NASA, 1984b) and the 1984 Earth System Science Committee Panel on Geophysics recommended the placement of several small Lageos-like satellites (mini-Lageos) into a variety of orbits with different altitudes and inclinations to study temporal variations in the Earth's gravity field. A study is planned to determine the optimum distribution of satellites needed to isolate resonant orbital effects and to detect the time derivatives of long wavelength spherical harmonic coefficients.

2. Geodynamics Laser Ranging System

A laser in orbit ranging to cube corner retroreflectors on the ground would, in principle, provide the same information as a large number of highly mobile ground lasers ranging to Lageos, except that only one laser would be required. The Geodynamics Laser Ranging System (GLRS) concept was initially proposed in the mid 1970's. In 1979, a workshop on spaceborne laser ranging (Institute for Advanced Study in Orbital Mechanics Report, 1979) recommended proceeding with development. An experimental version of the GLRS, the Shuttle Laser Ranging System (SLRS) was approved by NASA as a candidate New Start in the fiscal year 1977 budget, but was never funded. Studies of the SLRS indicated it should be possible to map the entire State of California at spacings of 20 to 200 km during one Shuttle flight (Kahn et al., 1980).

The global program of regional crustal deformation studies recommended by the Airlie House Geodynamics Conference re-introduced the need for rapid and frequent measurements in geographically separated and diverse regions. Studies of the costs of a ten-year program of global measurements using either GPS or a dedicated GLRS satellite (NASA, 1984d) showed the costs to be comparable. The study also showed that the GLRS costs could be reduced by about 40% if the instrumentation was included on a man-serviceable platform, such as the Earth Observing System (Eos). These conclusions have revived interest in the GLRS, and it is now a major aspect of the long-term NASA Geodynamics Program planning.

Currently, GLRS is being developed as a NASA-provided facility for Eos. Two-color laser ranging will be implemented using the green and ultraviolet pulses from a diode-pumped, frequency-doubled and tripled Nd:YAG laser transmitter. Streak-tube detection of the differential arrival time between the two pulses will allow for precise correction of the atmospheric propagation delay and thereby improve range precision to the several millimeter level. Simulations (Cohen et al., 1987) indicate that this system could be used to determine intersite distances to several millimeters accuracy over distances of several hundred to a thousand kilometers.

3. Geopotential Research Mission

Models of the Earth's gravity field now in existence are predicated on several data sources: radio frequency and laser tracking of Earth orbiting satellites; microwave altimetry; and ground-based measurements. None of these sources provide direct measurements of gravitational acceleration. These models have accuracies of 5-8 mgal for half wavelengths of 800 km. Over ocean areas, altimetry has been useful in mapping the ocean surface topography to 50 cm and, in the future, this mapping accuracy is expected to improve to 10 cm using TOPEX. Since altimetry cannot differentiate between ocean surface topography and the true mean sea level, or geoid-the difference being quasi-steady ocean currents - direct mapping of gravity is essential to both geodynamics and oceanography. Over the continents, ground measurements are known to an accuracy of about 1 mgal over $1^{\circ} \times 1^{\circ}$ averages for some 400 of the 44,000 square degrees on the surface of the Earth, and most of these measurements are for locations within the U.S., Europe, and Australia.

The lack of good gravity data was recognized as early as 1969, when a Gravity Field Satellite (Gravsat) was identified by the Williamstown Conference (NASA, 1969) as a high-priority mission for studies of Earth and ocean dynamics. The initial concept was based on tracking of a low orbiting satellite by a high orbiting satellite, or a "Hi-Lo" configuration. The feasibility of this concept was demonstrated in 1975 during the ASTP mission, during which the ATS-6 satellite was used to range to the Apollo-Soyuz spacecraft.

The Gravsat concept evolved after the successful demonstration of a single axis Disturbance Compensation System (DISCOS) on the U.S. Navy's Transit Satellites, and further studies into satellite-to-satellite tracking (SST). The DISCOS is based on a sphere floating inside a spherical cavity. When non-gravitational forces cause the sphere to move relative to the satellite, the velocity of the sphere relative to the cavity is sensed and the spacecraft is moved by reacting jets. Thus, the sphere is always in gravitational free fall. By tracking the relative motion in two such spheres in two separate satellites, using multi-frequency, coherent, radar systems, the variations in gravitational acceleration along the flight path can be measured. In the late 1970's, studies by GSFC and APL indicated Gravsat could provide global mapping of the gravity field to a few milligal for one-degree averages.

In 1978, an NRC Study (NAS, 1979) confirmed the need for accurate measurements of the gravity field and geoid for Earth and ocean studies. The NRC study noted the difficulty of processing the Gravsat data using existing methods: some eight million equations with 44,000 unknowns would have to be solved. To study this problem, a Gravsat Data Users Group was formed in 1980. This Group was eventually instrumental in developing several new methods which reduced this computational problem to reasonable proportions.

Following the success of the Magsat Mission, which like Gravsat benefited from a low orbital altitude, and in particular the development of a Magsat global map of magnetic crustal anomalies, magnetometers were added to Gravsat to obtain higher spatial resolution crustal data, and the mission was renamed the Geopotential Research Mission (GRM). To strengthen the scientific justification for GRM, a GRM Science Steering Group (GRMSSG) was formed in 1982 and produced in 1983 a document defining the scientific rationale for GRM (NASA, 1983c). This document was updated and revised in 1985 (NASA, 1985a). The GRMSSG also sponsored, along with NOAA, DMA, NSF and the USGS, a conference at the University of Maryland in October 1984 on the scientific uses of GRM data (NASA, 1985b).

As part of an on-going program studying improved techniques for gravity field determination, a new concept was developed by APL to combine the DISCOS and radar systems into a structure suspended within the spacecraft. This spacecraft within a spacecraft, or "Double DISCOS" approach, significantly reduced the complexity of GRM, since the disturbance effects of the outer spacecraft on the DISCOS are essentially eliminated. The results of some six years of GRM spacecraft and data processing studies have been compiled in a single report (NASA, 1986).

In 1986, ESA and NASA agreed to study the possibility of combining several missions into one: these included the GRM, the German POPSAT and the French GRADIO (Balmino et al., 1985). The studies showed that GRADIO could be integrated with the Double-DISCOS concept, but that a separate satellite would be needed for POPSAT. The preferred mission would use one high altitude satellite for POPSAT and the two GRM low altitude satellites. SST would be used between POPSAT and the GRM spacecraft (Hi-Lo SST) and between the two GRM spacecraft (Lo-Lo SST); in addition, GRADIO would provide a third set of gravity data. This mission proved too costly, and would provide only marginal improvement in measurement precision over GRM alone. Early in 1987, NASA management decided that GRM itself was too costly and proposed to ESA a new mission which would use a single spacecraft to carry GRADIO, the Double-DISCOS, a boom-mounted set of magnetometers, and a GPS receiver. Because of problems with the phasing of budget periods, ESA decided to proceed with studies of an ESA-only spacecraft based on GRADIO, and to leave open the option for NASA's participation in an enhanced mission which would include the Double-DISCOS, the magnetometers, and GPS. A decision as to which mission will be developed, if either, is expected later in 1988.

4. Gravity Gradiometers

A gravity gradiometer measures the differential motion of two masses separated by a finite distance in a varying gravity field: the GRM with its two separate spheres was essentially a gravity gradiometer with the masses separated by several hundred kilometers.

In 1980, a study was initiated with the University of Maryland (UMD) to develop a Superconducting Gravity Gradiometer (SGG) based on a cryogenic accelerometer developed earlier at Stanford University as part of research on gravity waves (Paik and Richard, 1986). The initial objective was to develop a three-axis gradiometer having a precision of 10^{-2} E $Hz^{-\frac{1}{2}}$ at frequencies of a few Hertz. A secondary objective was to test the validity of Newton's inverse square law of gravitation at meter scales.

A gradiometer of this precision would, if flown at an altitude of less than 200 km, provide measurements of the Earth's field comparable to GRM. The higher altitude (200 km versus 160 km for GRM) and the need for only one spacecraft could accomplish the GRM objectives at considerably lower costs, provided, of course, that the technology can be developed.

In the early stages, the SGG development was plagued by environmental noise problems. Considerable effort was required using two and three stage isolation to reduce the noise. In 1982, it was decided to limit the development to a single-axis unit until the instrument performance could be defined. Testing of the unit indicated a precision of 0.37 E $Hz^{-\frac{1}{2}}$ with an inherent lower limit of 0.07 E $Hz^{-\frac{1}{2}}$. A first attempt at verification of the inverse square law was made in 1982 using a large pendulum-suspended mass. The single axis gradiometer was mounted at 45° to the vertical, and sequentially rotated to measure the three components of the gravitational mass. This experiment succeeded in verifying the inverse square law within an experimental accuracy of about 1%.

Also in 1982, work was initiated with the SAO in conjunction with the University of Rome to develop a room-temperature capacitive-type gravity gradiometer, also derived from gravity wave research. A similar effort was started at GSFC to investigate the feasibility of using a tuned microwave cavity for gradiometry. This latter idea evolved from accidental discovery of the sensitivity of the supercavity clock to solid Earth tides.

As these gradiometer developments proceeded, interest turned towards ways of testing a gradiometer in space and the engineering difficulties of spacecraft designs and data processing.

Earlier, it was felt that the concept of a satellite tethered to the Shuttle could be applied to gradient measurements of the Earth's field. Because of its lower altitude, potentially as low as 140 km, the increased field strength would necessitate less instrumental precision. The lack of precise attitude control for a tethered satellite, its orbital motion, and difficulty in determining orbital position, appeared to limit the tether to experimental verification of instrument performance. Studies of the Space Shuttle raised similar concerns about environmental and crew-generated noise and variations in self-gravity due to mass changes, such as crew motion. A free flying spacecraft would either have to be spinning, very accurately controlled in three axes, or its attitude determined to high accuracy. The data processing appeared to be straight forward, but had not been studied.

To examine these problems, and to provide a forum for information exchange among the various instrument developers, a conference was held in early 1983 at GSFC. The Conference concluded, based on simulations performed by GSFC, that instrument performance should be limited to 3×10^{-3} E $Hz^{-\frac{1}{2}}$. The Conference identified study areas for flight systems and data processing and outlined a plan and budget for development, selection, and test of flight instruments (NASA, 1984a).

Based on the Conference, UMD modified the design of its gradiometer and improved the dewar and suspension system. Over the next few years, a six-axis cryogenic accelerometer which would fit in the central cavity of a three-axis gradiometer and a magnetic negative-length spring was invented by H. J. Paik of UMD. The accelerometer is to be used in a feed-back mode to correct for non-gravitational effects. The negative-length spring compensates for mass restraint and reduces the natural frequency of the system. To test the gradiometer a six-axis shaker which would fit in the dewar was designed.

Fabrication of components for the new gradiometer design was essentially completed in 1985 and assembly and testing began in 1986. Due to a series of technical problems, these tests continued through 1987. A photograph of the UMD SGG is shown in Figure III-17.

A feasibility study of an electromagnetic suspension system for flying a gradiometer in the Shuttle bay was undertaken by JPL in 1984 and is continuing. Initial results indicate it should be feasible to suspend a gradiometer package for some 20 seconds before torques would have to be applied. However, the attitude determination problem remains. In a separate effort, GSFC studied adopting a Spartan spacecraft, which was designed to be released and recovered during a Shuttle mission, for several days of free flight. However, the only Spartan spacecraft available was destroyed during the last Challenger flight.

Interagency interest in the UMD developments resulted in funding of the six-axis accelerometer by the AFGL and funding contributions from the U.S. Army Environmental Research Laboratories (ERL). To focus these developmental activities, a Gravity

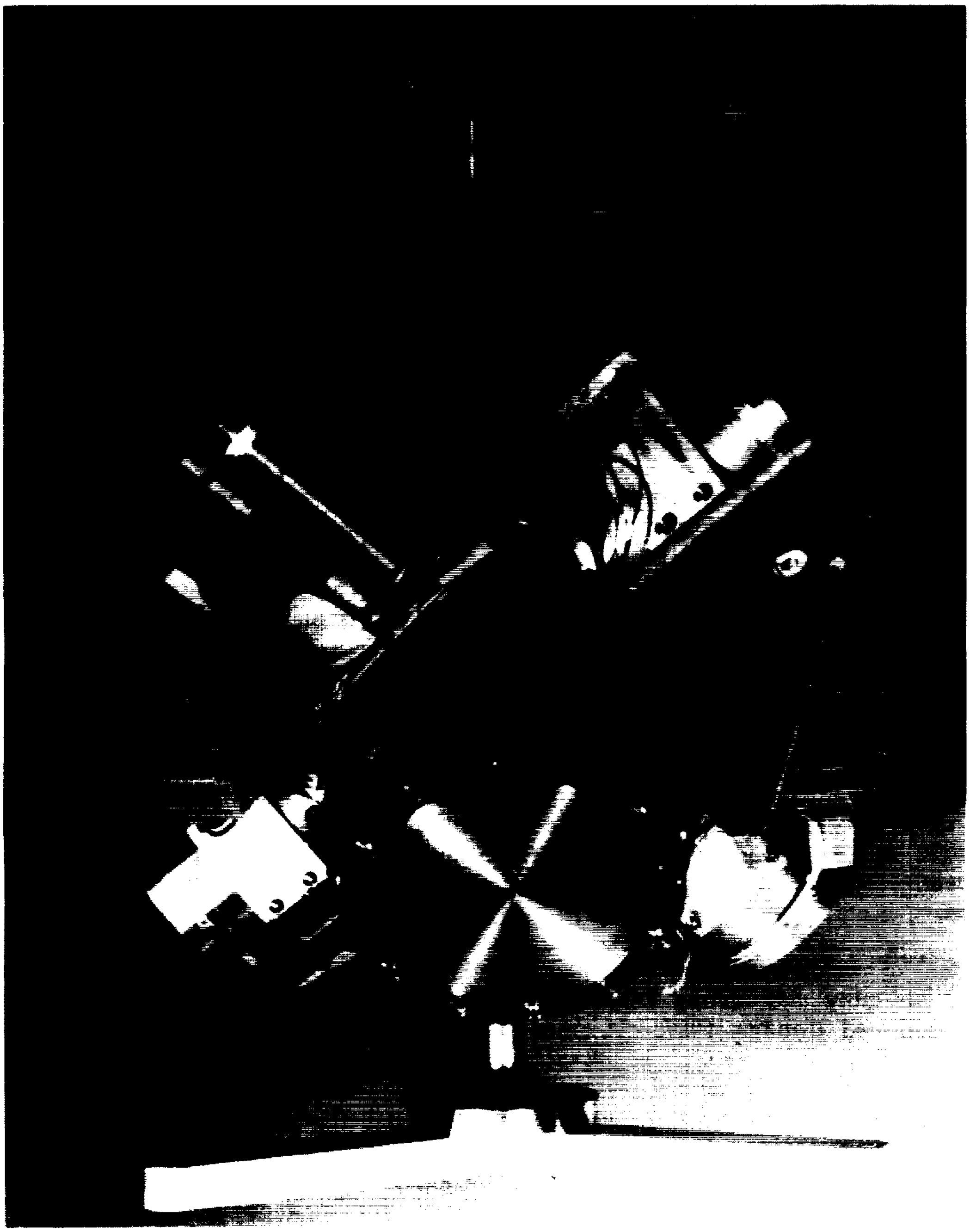

Figure III-17 Three-axis superconducting gravity gradiometer.

Gradiometer Study Team was organized in 1985 under the direction of MSFC. This team includes participants from UMD, GSFC, JPL, AFGL and ERL. One of the objectives of the Study Team is to formulate plans for tests of the gradiometer in space. The Study Team Report is expected to be released in 1988.

Depending on the resolution of the NASA/ESA discussions, a Superconducting Gravity Gradiometer Mission (SGGM) is planned to follow the joint NASA/ESA mission sometime in the latter part of the 1990's. The SGGM would be capable of measurement accuracies, for half-degree squares, of about an order of magnitude better than either GRADIO or GRM could be expected to achieve.

In a separate vein, the technologies evolving from the gradiometer development have high potential for application for control of ballistic and orbital flight and for very precise determination of orbital attitude.

5. Magnetic Field Explorer

The first satellite specifically dedicated for studies of the Earth's magnetic field was the Magnetic Field Satellite (Magsat). Launched in October 1979 by a Scout vehicle, Magsat re-entered the atmosphere in July 1980. Shortly thereafter, plans were devised for a follow-on mission for continued study of the main magnetic field. Designated Magsat-B, this second mission was intended to study secular variations of the field over a period of three to five years. These objectives were examined by a Magnetic Field Workshop held at GSFC in 1982 (NASA, 1982c).

In 1983, articles from French researchers, based on ground magnetic observatory data from stations in Europe, postulated the occurrence of sudden accelerations of the westward drift of the main field in 1906 and 1969 (magnetic "jerks"). The "jerks" appeared to be correlated, but out of phase, with variations in the LOD.

In 1983, a Magnetic Field Survey Working Group was established to re-examine and to define the mission objectives and parameters for the MFE (NASA, 1984c). Almost concurrently, a non-government advocacy group, the International Working Group for Magnetic Field Satellites (IWGMFS), was formed and held its first meeting at the 1984 Spring AGU Meeting.

Pre-Phase A studies of the MFE, based on Magsat-1, were started by GSFC and APL in 1984. Changes from Magsat-1 required to extend mission lifetime were studied. One of these included the feasibility of using star cameras instead of the Magsat-1 optical platform to determine the three-axis orientation of the boom-mounted magnetometers. The studies indicated that because of its weight, a Scout-launched MFE could not reach the 600 km altitude needed to sustain a three-year lifetime near the 1992 solar maximum.

A second study was initiated in early 1985 to examine the feasibility of adapting the Shuttle-launched Earth Radiation Budget Experiment (ERBE) spacecraft for the MFE mission. The ERBE spacecraft had the advantages that a higher orbit could be achieved and that it was retrievable by the Shuttle. This introduced the possibility of using the same spacecraft for an extended mission lifetime of a decade or more: the disadvantage was the higher initial spacecraft cost.

Studies were also started at GSFC on the feasibility of using an upgraded Spartan spacecraft which would be left in orbit by the Shuttle and retrieved after an extended period. MFE/Spartan flights once or twice each year could also provide the main field data needed.

Concurrent with the NASA activity, researchers in France recommended that their government initiate plans for a French magnetic field satellite - Magnolia. As a result of a management-level NASA/CNES meeting in 1984, a NASA team visited CNES to explore possible NASA/CNES cooperation on magnetic field satellites. This was followed by the first meeting of a formal NASA/CNES Study Group in late 1984. A joint Magnolia/MFE Phase A study was completed in early 1987. NASA and CNES are proceeding with Phase B studies, which could lead to a joint mission with a piggyback launch on an Ariane launch vehicle sometime in 1991. A Phase B Study Report on the MFE/Magnolia mission will be published in 1988.

The requirements for main field studies are for long-term measurements of a decade or more. A single satellite can be expected to function for three to five years. Since the Eos will be man-tended and in a polar orbit of 600-800 km, it would be an ideal candidate for continuation of these studies into the next century. However, to place the magnetometers in an area sufficiently free of the magnetic field background of the Eos, either a very long boom or a tether would be required. For stability, the minimum length for a tether is several km. Studies of an Eos tether and the feasibility of using it for scalar and vector field measurements have been initiated at GSFC.

6. Tethered Satellite System

The concept of tethering a satellite to the Shuttle was initially conceived by the SAO for magnetospheric studies. However, because of the possibility of using the tether for near-Earth (140 km altitude) gravity and magnetic field measurements, the Geodynamics Program supported dynamical studies of long tethers by the SAO for several years. This eventually evolved into a joint NASA/PSN Agreement for development and use of a Tethered Satellite System (TSS). Under this Agreement the PSN is to design, develop, and build the spacecraft. NASA will design, develop, and build the reel system and deploy the tether from the Shuttle. The second flight of the tether in the early 1990's would involve downward deployment to some 100 km from the Shuttle.

In 1983, in response to an Announcement of Opportunity, a joint SAO and University of Rome single-axis gravity gradiometer experiment was selected for development for the second TSS flight (Gullahorn et al., 1985). Accelerometers and gyros are to be included on this flight to provide additional data for assessing future use of the TSS for gradiometry experiments. In 1987, an Italian experiment for Magnetic Field Studies was selected for the first TSS flight in the fall of 1990.

7. Shuttle Time and Frequency Transfer

Accurate time and frequency coordination is an essential aspect of many scientific experiments and operational systems. The most accurate time standard is the hydrogen maser. To standardize time, "live" clocks are frequently transported around the world by air. Time transfer can be accomplished with VLBI (which solves for time differences at each station), by laser ranging to a satellite equipped with photodetectors and a time interval counter (the ESA LASSO experiment), or by recorded transmissions from GPS.

The VLBI and laser methods are limited to sites having these systems. The GPS accuracy is nominally 20 ns, although isolated incidences of accuracies of a few nanoseconds have been reported.

In 1979, it was proposed that a hydrogen maser clock be flown on the Shuttle to demonstrate time transfer to better than 1 ns and frequency synchronization to one part in 10^{14} per day. The transfer would use the three-way Doppler method developed and used for Gravity Probe A. Laser ranging at select sites would be used to verify the time transfer accuracy.

A study team was formed and included MSFC, SAO, UMD, USNO, and NBS. The studies were continued through 1984, and essentially terminated in 1985.

IV. OUTLOOK

A. CRUSTAL DYNAMICS

The development of space geodetic instrumentation with yet improved precision and greater mobility will open unexplored avenues of research on the dynamics of the Earth's crust and upper mantle. In order to accomplish this, the CDP Investigators' Working Group, at its March 1987 meeting, laid out the following performance goals for future measurements:

- To contribute to the improvement of existing models of present-day motions among the major plates, the tangential components of relative velocities on interplate baselines must be resolved to an accuracy < 3 mm/year.
- Measuring velocities between crustal blocks to $\pm$ 5 mm/year can place geologically useful constraints on the integrated deformation rates across continental plate-boundary zones such as the western United States.
- To detect the horizontal motions associated with the secular deformation of stable interiors, the tangential components of intraplate baselines must be resolved to an accuracy of < 1 mm/year.

The potential of this improved observational capability can be considered in greater detail in terms of the programmatic objectives in global plate motions, plate boundary deformation and intraplate deformation. High priority site locations from which the observations should be made are listed in Table IV-1.

1. Global Plate Motions

As a result of the CDP, precise measurements of the contemporary rates of interplate motions are being obtained directly for the first time. In general, these rates compare fairly well with time-averaged rates which can be obtained only indirectly from magnetic anomalies on the sea floor, the record of reversals of the Earth's magnetic field, and the movement of hot spots. However, these are averages of rates over the last few million years and, as evidenced by earthquakes, movement is episodic, at least near active plate margins. The increased precision of space-based measurements raises the possibility of assessing the time-varying rate of movement. This rate, determined as a function of distance from the plate boundary, will be important in the development of models of the rheology of the lithosphere.

Thus, a major future challenge will be to test whether the long- and short-term rates of plate motion are equal, and to determine the length scale over which episodic slip at plate boundaries is damped out to steady motions.

Fast-moving plates should be most sensitive to any time variations. The primary measurements required to support investigations in this area include:

- Absolute and relative rates of motion of the tectonic plates at sampling intervals of one month to one year and distance scales of 100 to 10,000 km;
- Absolute vertical motion at sample intervals of one month to one year and

TABLE IV-1

CRUSTAL DYNAMICS SITES FOR PRECISE POSITIONING OBSERVATIONS

1. Variation in rate of plate motion
   - Nazca-Pacific Plates
   - Nazca-South American Plates
   - Pacific-East Asian Plates
   - Australian-Indo-Eurasian Plates
   - Pacific-North American Plates

2. Strain at plate boundaries
   - Normal convergence
     - Aleutians
     - Japan
     - Peru
   - Complex convergence
     - Himalayas-Tibet-China
     - California Transverse Ranges
     - Aegean
     - Australia-Borneo-Timor
     - Iran
   - Continental divergence
     - East Africa-Red Sea-Gulf of Aden
     - Rio Grande Rift
     - Rhine Graben
     - Back-arc basins

3. Plate rigidity
   - North American Plate (10 stations)
   - Indo-Australian Plate (2 stations in Australia, Sri Lanka and India)
   - Pacific Plate (6 stations on widely distributed islands)

4. Vertical motion
   - Himalayas
   - Southern California
   - Basin and Range province, U.S.

5. Regional tectonics and crustal hazards
   - Western U.S.
   - Western Alaska
   - North Anatolian Fault (Turkey)
   - Alpine Fault (New Zealand)
   - Andes (Central, South America)
   - Tonga-Fiji-Kermadec-New Zealand region
   - Caribbean
   - Mediterranean

over distance lengths of 10 km and greater;

- Earth rotation parameters (pole position, UT1) at intervals of one day (occasionally at 6-hour intervals) with accuracies of 1 mas and 0.1 ms, respectively;
- Dense net relative positions of 10^4 square kilometer areas with single baseline distances of 10 km to 100 km at irregular intervals (occasionally, as rapid as one day intervals).

Because most plate boundaries are under water, a full understanding of the forces which drive and resist plate motion requires an ability to make geodetic measurements on the sea floor. Such measurements are possible using the two-way travel time of acoustic signals between a set of transponders mounted on the sea floor and a surface buoy. A GPS receiver on the buoy allows the positioning of the sea floor reference point with respect to a global geodetic grid (Spiess et al., 1983).

2. Plate Boundary Deformation

A major earthquake is generally followed by deformation in the region lasting over periods of years. Through the study of such post-seismic deformation, it is possible to determine the viscous properties of the crust and mantle. For this reason, it will be important to measure the time-dependent deformation in a number of the major worldwide seismic zones. This will also address the questions of the coupling between motions in the mantle and deformation of the crust and the distribution of stress and strain across fault zones as a function of lithospheric type (continental or oceanic). The measurement of deformation at plate boundaries is also related to the goal of understanding the earthquake cycle and its relation to stress, strain rate, fault structure and the conditions under which major earthquakes display diagnostic precursory phenomena.

Measurements of deformation at plate boundaries would also shed light on questions relating to the evolution of island arcs, the dynamics of mountain building at convergent boundaries and the growth of the continental crust with time.

3. Intra-Plate Deformation

An important question in tectonics is why large areas of continents have been slowly uplifted as broad plateaus while others have subsided to become basins. The origin of these movements within plates and their relationship, if any, to forces at plate boundaries are not generally understood. We do not know why the continental crust sometimes spreads and drops into rifts; why some rifts fail (i.e, cease to open) and others form ocean basins; nor do we know the influence of igneous activity on the rifting process and vice versa.

Dynamic models of plateau uplift, based on geodetic measurements of uplift rates, must be tested against improved thermal, seismic and potential field data. Flexure of the lithosphere as it responds to geologic loads (e.g., volcanic islands) provides information on the mechanical properties of the Earth's lithosphere. Determination of the peripheral uplift, or subsidence pattern, in areas of recent deglaciation and in coastal regions would permit an improved determination of the radial viscosity profile in the Earth's mantle and an estimation of lateral variations in mantle viscosity.

Investigation of the deformation of plate interiors initially requires precise geodetic positional determination at several locations within the plate with spatially more detailed measurements in and adjoining areas of specific tectonic interest.

B. EARTH ORIENTATION STUDIES

Monitoring of the Earth's orientation by VLBI, LLR, and SLR will continue for many years. This data base will undoubtedly yield new, perhaps unexpected geophysical insights comparable to those already achieved. Each system determines the orientation of Earth relative to object(s) it tracks in the sky, and also provides position histories of these objects. The information obtained from each system is sometimes complementary, resulting in a deeper understanding of the underlying mechanisms. Analysis of combined data sets within a single analytical system would take best advantage of such complementarity.

For example, LLR determines the recession of the Moon which is primarily due to tidal dissipation in shallow seas. The present estimate of the rate of change of lunar mean orbital angular velocity is -24.9 ± 1.0 arcseconds/century^2, equivalent to 3.7 ± 0.2 cm/year in distance. The uncertainty of this measurement will be reduced to less than 0.5 arcseconds/century^2 by 1990. Lageos' orbit is also perturbed by the Earth's dynamic tidal gravity field, sensing the amplitudes of individual tidal constituents.

Lageos and other satellite data can be used to independently predict the lunar recession rate. A preliminary satellite solution for lunar acceleration from solid tides is -25.3 ± 0.6 arcseconds/century^2. Comparing the Lageos data with the lunar measurement will indicate if there is a significant non-Earth-tide component of lunar acceleration. These data can then be compared with estimates of lunar dissipation caused by solid friction and core-mantle friction, consistent with the observed lunar libration signature. The solid friction mechanism predicts a small but measurable 0.4 arcsecond/century^2 contribution to lunar acceleration, while that from core friction is several times smaller.

Other combinations of data could reveal the fraction of tidal dissipation due to solid friction in the Earth. The vertical motion represented by the principal tidal constituents can now be estimated with about 1% uncertainty by the IRIS network. A modest improvement in this system together with more data may reveal the phase lag caused by solid friction if the contribution from ocean tides can be accurately removed using existing tidal models. The planned TOPEX mission, among other things, will obtain topographic maps of the major tidal constituents. The solid Earth elastic model constructed from seismic data indicates a 1% decrease in mantle rigidity in the 1 to 3000 second period band. This effect is attributed to anelastic dispersion. Models for this dispersion predict that there may be an additional 1% increase at diurnal frequencies and could be as large as 10% for the 18.6 year zonal tide. The complementary tidal data from each of these systems will eventually determine Earth's solid friction parameters.

This example, which is not necessarily the most important science in this field, does illustrate how these systems can interact in attacking a problem. The projected major advances of geophysical interest will come in areas which have been previously discussed:

1. Monitoring of Earth's nutations and improvement in the nutation model. This effort should improve understanding of core- mantle coupling mechanisms, especially the role of the non-hydrostatic ellipticity and its compatibility with models of mantle convection. Detection or substantial reduction of the FCN mode should be possible given more data and an improved forced nutation model.

2. Monitoring of Lageos' nodal residuals. This work will verify whether the apparent acceleration is secular or has a long-period (18.6 year) component. These data, together with improved solutions for secular polar wander, will continue to impact studies of post-glacial rebound and models of the Earth's rheology. Research in this area is likely to promote interest in mapping changes in the Earth's gravity field through a future dedicated mission.

3. Monitoring and Analysis of LOD and Polar Motion. This effort would stimulate further research involving global atmospheric models, ocean loading response models, seasonal distribution of surface water and core-mantle coupling mechanisms. A clearer understanding of the excitation and damping mechanisms for the Chandler wobble should emerge.

It is also anticipated that sometime within the next ten to twenty years mass displacement associated with very large earthquakes, comparable in magnitude to the 1960 Chile or 1964 Alaskan earthquakes, will be detected through both a displacement of the pole and a secular change in the Lageos node rate. Although the fulfillment of this prediction depends on the whim of nature, this information will be of value in testing fault models and verifying seismic moment calculations.

The discussion of projected science achievements is by no means complete. However, there is reasonable certainty that the forthcoming science generated from orientation and dynamic gravity field variations will be impressive and should contain several unexpected scientific returns.

C. GEOPOTENTIAL RESEARCH

1. Gravity Field and Geoid

The recent report of the Gravity Field Workshop sponsored by NASA (NASA, 1987) presents a broad perspective of the contributions which can be made through detailed measurement of the global gravity field and specifies the observational parameters required.

Detailed knowledge of the global gravity field will provide valuable insight into the properties of the whole Earth. In conjunction with other data, it can contribute to the solution of fundamental questions such as:

- The structure of the oceanic lithosphere and its interaction with the aestheno-sphere;

- The density structure of adjacent lithospheric plates across oceanic fracture zones;

- Whether subducted slabs penetrate into the lower mantle;
- The depth of compensation of oceanic plateaus to determine continental vs. oceanic origin;
- The thermal structure of the continental lithosphere;
- The origin of continental rifts;
- The forces or mass concentrations causing basin subsidence;
- The mechanical strength of the continental lithosphere;
- The depth of continental roots;
- The composition and rheology of the mantle and the scale of its convection;
- The origin of seismic velocity anomalies;
- The existence of small-scale convection cells beneath lithospheric plates.

In addition, determination of the gravity field as it varies as a function of time will help:

- Improve tidal models for the solid Earth and oceans in order to better understand tidal loading;
- Determine lateral and vertical variations in mantle viscosity through observation of the effects of glacial rebound;
- Measure the gravity signal from vertical ground movements before and after volcanic eruptions and earthquakes in order to study geologically rapid mass movements.

To enable these advances, several developments are underway or proposed.

Development of the Interim Gravity Field Model is expected to be completed over the next 3-4 years. A goal is to produce a model which is a factor of two or three better than GEM-10B. This model should also spur further research into large-scale mantle convection, although the accuracy needed for more detailed studies must await the first gravity field satellite mission.

The TOPEX mission was approved as a new start in fiscal year 1987, and should be launched in 1991. The sea surface topography determined with the improved TOPEX altimeter should have a precision of 2-10 cm. These data would provide moderate improvement to gravity field models, since the ocean gravity is reasonably well known from previous altimeter missions. However, these data would be useful for continued studies of ocean bottom topography. Data similar to TOPEX, but of less precision, will be acquired by several other missions planned for launch in the early 1990's. These include the Navy Research Oceanographic Satellite System (NROSS), the ESA ERS-1 and ERS-2, and the Japanese ERS-1.

The earliest launch date for a gravity field satellite mission, either as an ESA GRADIO mission or a NASA/ESA mission, will not be before mid-1993. Shuttle tests of a superconducting gravity gradiometer are planned for the mid-1990's, and could provide new gravity data of substantially improved accuracy. In the latter 1990's, a new level in gravity measurements from space will be attained with the Superconducting Gravity Gradiometer Mission (SGGM).

2. Magnetic Fields

a. Main Field

It is fair to say that main field geomagnetism has reached the point where accurate global vector data extending over a significant time span are required for further advances. These type of global data are most readily obtained from space. To study the fluid core, mantle conductivity, and time changes in external fields, requires not just a snapshot of the field, as was achieved by Magsat, but a global time history of the field. The temporal spectrum of interest includes periods from months to decades.

Because magnetic field lines must pass through the mantle, a study of the Earth's main field yields information both on the conductivity of the mantle as well as of the core. In these studies, the temporal variability of the geomagnetic field is at least as important as its description at a particular epoch. These temporal variations occur over periods from months to decades and, as a result, require continuous and long-term measurements for adequate characterization.

The secular variation of the main field is believed to be due to motion of the fluid in the outer core. Therefore, data on the secular variation provide crucial information on the kinematics of this motion and produce a starting point for understanding its dynamics.

On the time scale from years to decades, there may be a correlation between the secular variations of the magnetic field and variations in the LOD. Such a variation could be accounted for by electromagnetic coupling between the core and the lower mantle. If such a correlation could be established, it would give important information on the conductivity of the lower mantle and on the strength of the toroidal field at the core-mantle boundary.

A plan for this research has been mapped out by the International Working Group on Magnetic Field Satellites. This plan is predicated on new measurements beginning as soon as possible to maximize the utility of combining them with the Magsat data. To support this requirement, NASA is studying both an MFE which would be similar to Magsat, but of longer duration, and a combined MFE/Magnolia mission with CNES. As separate missions, MFE could probably be launched in 1991 and MFE/Magnolia mission in 1992. MFE/Magnolia, with a five-year lifetime, would continue to operate into the era when decade-long measurements will be possible from the Eos polar-orbiting platform.

b. Crustal Field

The Magsat crustal magnetic anomaly maps have provided new insight into the association of residual magnetism with large scale geological features and tectonic processes. The spatial resolution of the Magsat data is of the order of 300 km, and questions remain as to the contamination of these data by high-frequency (order of 13 and above) components of the main field. Higher spatial resolution is required to better define the magnetic structure of faults, sutures, and back-arc basins associated with subduction. Such data should also prove useful for geological resource assessment.

The limiting factor in resolving the magnetic signature of structures in the crust is the altitude of observations (Webster et al., 1985). Spatial resolution is qualitatively defined as the ability to distinguish, as separate entities, two bodies of equal magnetization and shape separated and surrounded by material of different magnetization. A model which illustrates the point is shown in Figure IV-1. In this model, two identical bodies (200 km x 200 km in area and 40 km thick) are given equal magnetic susceptibilities which contrast with the surrounding volume. The distance between the bodies, d, and the height (altitude) of the observations are varied. The effect of two other variables which influence resolution is also considered: (1) the location of the bodies on the Earth (accounting for the variation of field strength and inclination over the Earth), and (2) the orientation of the two bodies with respect to magnetic north.

Using this model, the resolution as a function of altitude for two bodies separated by 450 km has been calculated for previous and proposed missions. In Figure IV-2 are shown: POGO (flown from 1965 to 1971) between 400 and 1500 km; Magsat (flown in 1979-1980) between 325 and 550 km; GRM at 150 km; and payloads tethered from the Shuttle to as low as 100 km. For this separation, the gain in resolution afforded by the lower altitude of a GRM-like mission compared to Magsat is about an order of magnitude.

NASA has proposed that a joint NASA/ESA gravity field mission should be flown at an altitude similar to that planned for GRM and should include magnetometers for crustal field studies. Such a mission will probably provide the highest resolution crustal magnetic field data obtainable from space. At the proposed altitude, the resolution of the magnetic field data will be at least comparable to the approximate 100 km resolution of the gravity data. Thus, we would have available both magnetic and gravity data for the entire planet, at the same resolution and taken at the same time, for global study of geophysically and geologically interesting crustal structures.

If the MFE (or Magnolia/MFE) satellite were in orbit at the same time as the gravity field mission, the main field measurements at the higher altitude of the magnetic field mission could be used to extract the crustal field data from the lower-altitude magnetic field measurements. This would be helpful in addressing the issue of main field contamination, since the field measured by the higher-altitude satellite would be considerably less sensitive to the shorter wavelength main field components. Also, the simultaneous, or near simultaneous, measurement of the field at two altitudes would allow an initial test of the feasibility of using magnetic gradiometry to determine the depth of the source of the magnetic anomalies.

While the altitude for the Tethered Satellite System (TSS) is less than for a free orbiting satellite, it is highly probable that tether dynamics will limit measurements of the magnetic field to only scalar field measurements. The lack of vector field measurement would limit the usefulness of these data for crustal studies. However, the TSS measurements are important for another purpose. Studies of Magsat data have revealed a bias in the crustal anomalies which may be associated with orbital inclination. The TSS data would be obtained at a different inclination and would be invaluable to understanding this effect.

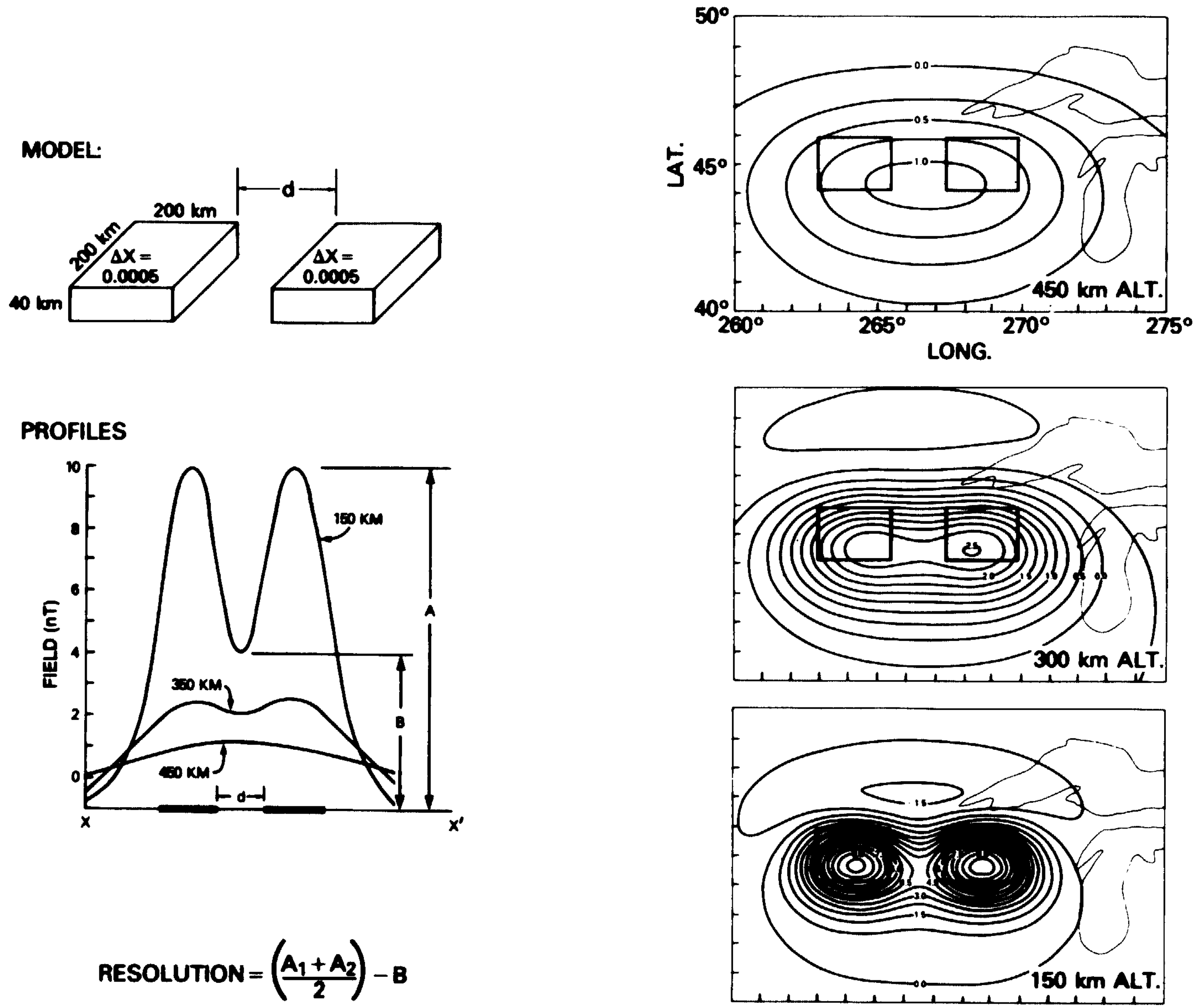

Figure IV-1 Results of calculations illustrating the capability to observe two separate two magnetic masses using a satellite magnetometer as a function of satellite altitude.

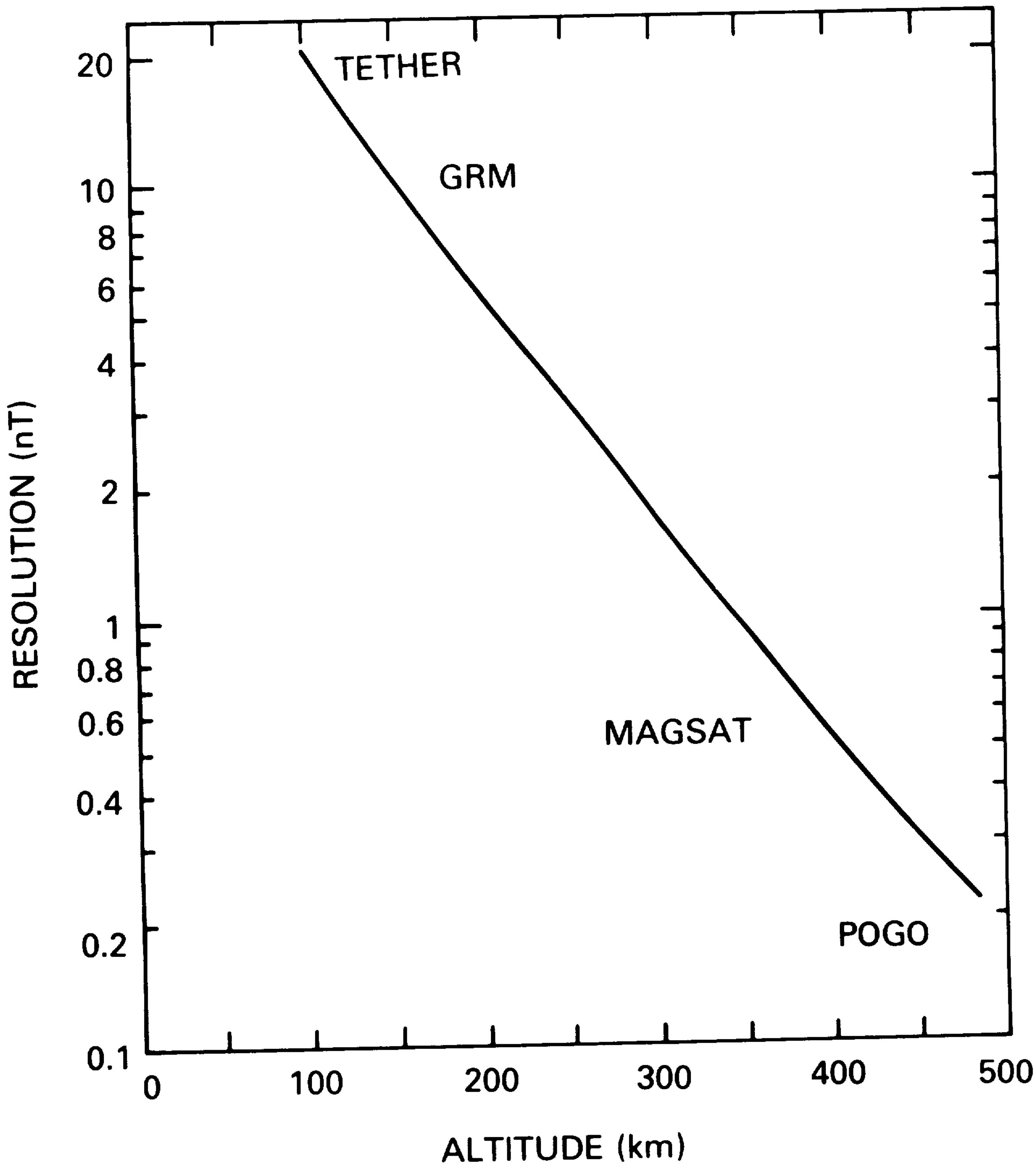

Figure IV-2 Resolution of magnetic crustal anomalies for satellite missions.

V. PROGRAM CHRONOLOGY: 1979-1987

A. 1979 - 1980

1. The CDP was organized; GSFC was authorized to manage the operational aspects of the program; and the CDP Plan was approved.

2. An agreement was signed between NASA, NOAA, USGS, NSF and DMA establishing an Interagency Program for the Application of Space Technology to Crustal Dynamics and Earthquake Research.

3. Sites were selected in tectonic areas for SLR and VLBI measurements of crustal deformation.

4. Fifty-five and fifty-nine independent baselines were measured using both SLR and VLBI in 1979 and 1980, respectively.

5. Construction of a dedicated LLR/SLR facility at McDonald Observatory to replace the LLR operations on the 2.7-meter astronomical telescope was initiated.

6. TLRS-1 was completed by the University of Texas at Austin and deployed for measurement intercomparisons with MV-1.

7. SAFE was repeated using both SLR and VLBI techniques. Analysis of the laser observations showed the baseline length between sites as decreasing at a rate of approximately 8 cm/year.

8. Measurements of crustal deformation were begun in southern California using MV-1.

9. The Mark-III VLBI system became operational and was used to carry out a five-station experiment between the U.S. and Europe.

10. VLBI achieved 4 cm repeatability in the determination of transcontinental baselines, and the short MERIT campaign recovered Earth rotation with a formal error of 2 mas in pole position, and 0.2 ms of time.

11. A five-station SLR/VLBI intercomparison showed agreement to 5 cm.

12. The 1980 Project MERIT observing campaign was supported by NASA SLR and VLBI facilities.

13. A formal agreement was concluded with Japan to undertake joint VLBI experiments.

14. The CSTG was established by the IAG. ICSU approved a request from the IUGG to establish the ILP for the 1980's as a follow-on to the International Geodynamics Project of the 1970's.

15. An AO for Crustal Dynamics Data Use was issued in October 1980: approximately 90 proposals were received.

16. Twenty-six domestic investigators were selected for Lageos-I data analysis. Twenty-seven were selected to participate in the Geodynamics Research Program, and thirty-two were selected for participation in the Magsat Project.

17. Magsat was launched and re-entered the Earth's atmosphere some seven months later: An initial magnetic field model was produced.

18. A Gravsat User Working Group was formed by NASA and a Federal Gravsat Panel developed a plan for joint agency participation in the Gravsat mission (NASA, 1980c).

19. A brassboard model of the Gravsat SST system and simulations of the Disturbance DISCOS system were initiated: simulations of gravity field recovery with Gravsat indicated a gravity field model improvement of two to three orders of magnitude.

20. IAU Colloquium No. 55: Reference Coordinate Systems for Earth Dynamics, was held in September 1980.

21. An interagency plan for geodetic use of the GPS satellites was prepared (NASA et al., 1980e) and a plan for laser development was published (NASA, 1980e).

B. 1981 - 1982

1. Baseline measurements were initiated in the western U.S. from 23 sites, using mobile SLR and VLBI stations, for crustal deformation studies.

2. Analysis of the VLBI-determined baseline between Westford, Massachusetts, and Owens Valley, California, showed no detectable change in baseline length within $\pm$ 0.5 cm/yr.

3. Interplate baseline measurements were continued using fixed laser and VLBI stations located on the North American, South American, Australian, Pacific, and Eurasian Plates.

4. TLRS-2 was completed and deployed to Easter Island. Laser (Moblas) stations were established in French Polynesia, and at Mazatlan, Mexico.

5. A contractual agreement was implemented with Natmap for upgrade of the Orroral Valley, Australia, LLR station and its incorporation of SLR capability.

6. An agreement was concluded with the PSN of Italy for cooperative geodynamics activities including: a laser site at Matera, Italy; studies for highly mobile SLR system development; and a joint Lageos-II mission.

7. A NASA/PSN Lageos-II Study Group recommended (NASA/PSN, 1983b) that Lageos-II be the same as Lageos-I, and launched into a 6,000 km circular orbit with an inclination of 52°.

8. The Westford, Massachusetts, POLARIS station was completed and NOAA

initiated routine measurements of polar motion and UT1.

9. Agreement was demonstrated between determinations of polar motion using SLR, LLR, and VLBI.

10. A very strong correlation was demonstrated between changes in the measured LOD and changes in AAM computed from global weather data.

11. The first MERIT Workshop (May 1981) was held in conjunction with IAU Symposium No 63 on High-Precision Earth Rotation and Earth-Moon Dynamics.

12. The selection of 57 CDP Investigations was completed, including 16 from other countries.

13. A new gravity field model GEM-L2 (Lerch, 1982) was developed using Lageos-I tracking data: this improved the precision of baselines and polar motion/UT1 measurements by a factor of two.

14. Analysis of the Lageos-I orbit identified variations in J_2 which agreed with theoretical estimates of the changes in the Earth's gravity field due to the effects of post-glacial uplift.

15. Studies of the GRM show tracking accuracies of better than 0.3 micron/sec and the GRMSSG was established.

16. The first vector field model of the Earth's main magnetic field and maps of crustal magnetic anomalies were developed.

17. GPS geodetic receiver development moved into test phases: repeatabilities of 6 cm or less were obtained for short baselines; the major source of error was identified as uncertainties in determination of the orbits of the GPS satellites.

18. In response to a Geodynamics Notice, 93 research proposals were received and 32 were selected for funding.

19. The Federal Implementation Plan for Crustal Dynamics and Earthquake Research was approved by the ICCG (ICCG, 1982).

20. Workshops were held on the Earth's gravity field (NASA 1982c) and magnetic field (NASA, 1982c); and a Geopotential Research Plan (NASA, 1982a) developed to guide this research over the next decade.

C. 1983 - 1984

1. The Geodynamics Branch of the Earth and Planetary Exploration Division was integrated into the newly formed Earth Science and Applications Division of the Office of Space Science and Applications.

2. Changes in interplate baseline lengths determined using SLR and VLBI were found to be in general agreement with the Minster-Jordan model.

3. The SLR measured rate of movement along the Quincy - Otay/ Monument Peak, California, baseline combined with the rate of spreading in the Basin and Range Province (based on available geological data) was used to infer rates of motion on off-shore faults west of the San Andreas.

4. The Matera, Italy, SLR station became operational and an agreement was signed with Israel for the loan of a NASA SLR system.

5. The Orroral Valley, Australia, station began SLR operations.

6. Initial measurements were obtained between Baja California and Mazatlan, Mexico; and across the subducting area associated with the Nazca and South American plates.

7. Advanced lasers were installed in several Moblas stations; work was begun on fabrication of TLRS-3 and -4; and TLRS-1 and -2 were withdrawn from the field to investigate several problem areas.

8. The first VLBI measurements were obtained in the Pacific and Alaska using fixed and mobile systems; the Japanese RRL VLBI Station at Kashima became operational.

9. Cryogenically-cooled receivers were installed on VLBI systems; work was started on a faster correlator, high data density recorder tape heads, and redesign of WVR's.

10. Operational responsibility for MV-3 and the VLBI station at Mojave, California, was transferred to NOAA.

11. An interagency agreement was implemented to establish a VLBI correlator in Washington, D.C.

12. The POLARIS Network, developed cooperatively by NOAA and NASA, was placed into operational use and an agreement concluded for POLARIS to provide data to the CDP.

13. The POLARIS/IRIS Network and the global network of fixed satellite and lunar ranging stations participated in the international MERIT Project.

14. Analysis of LOD variations for 1983 showed that AAM changes associated with the 1982 - 1983 El Nino decreased the LOD by about 5 ms.

15. The Second MERIT Workshop was held (May 1983), and the Main MERIT Campaign was conducted from September 1983 to October 1984. The first COTES intensive campaign was held from April to June 1984.

16. Agreements were concluded: with Austria for laser data exchange; with Japan for long-term Pacific Plate motion measurements; and, through the European WEGENER Consortium, with Turkey, Egypt, and Tunisia.

17. Satellite Emission Range Inferred Earth Surveying (SERIES) units measured the baseline from Owens Valley to Mammoth Lake, California, for comparison with

mobile VLBI systems; and the first interagency GPS tests were conducted.

18. A tri-agency agreement was drafted for determination of GPS orbits using a fiducial concept.

19. A Caribbean research study was initiated based on using GPS.

20. Studies of the along-track acceleration of Lageos-I indicated that Earth albedo radiation asymmetry could be a source of this perturbation.

21. An agreement was concluded with Italy for the fabrication and launch of a Lageos-II.

22. GRM studies continued and a new concept - a double-DISCOS was investigated.

23. Work was started on an interim gravity field and the conversion of GEODYN to run on a Cyber 205.

24. Initial tests of a single-axis cryogenically-cooled gravity gradiometer demonstrated a precision of 0.3 E $Hz^{-1/2}$ and the instrument was used to verify the inverse square law of gravitation at meter distance scales.

25. Conceptual studies were conducted of a Scout-launched MFE for studies of the main magnetic field and its secular variations.

26. In a related program, an agreement was signed by NASA and the Italian PSN for the TSS.

27. A Geodynamics Conference at Airlie House, Virginia, and a Gravity Gradiometer Workshop at GSFC were held in 1983 to study long-term planning, and reports were issued in 1984 (NASA, 1984b and NASA, 1984a, respectively); a GRM Science Conference was held at the University of Maryland in 1984.

28. The Earth System Science Committee (ESSC) was formed by NASA to develop an integrated Earth Science Plan; the Geophysics Panel of the ESSC met in southern California in late 1984 to develop the geodynamics portion of the plan.

D. 1985

1. Measurements of global plate motion were continued using SLR and VLBI networks.

2. Measurements of the regional deformation of the North American plate, including Alaska and Mexico, were continued.

3. The International Conference on the MERIT-COTES Campaign on Earth Rotation and the Terrestrial Reference Frame was held at Columbus, Ohio, to review the results of the measurements made by different techniques. It was concluded that the VLBI, SLR, and LLR techniques were at least 10 times more accurate than the conventional optical and Doppler techniques for determining

Earth rotation and polar motion.As a result, the MERIT Project recommended to the IUGG and IAU that a new International Earth Rotation Service (IERS) be established based on VLBI, SLR, and LLR. The IERS would replace the BIH.

4. MTLRS-1 was collocated with Moblas-7 at GSFC and both MTLRS-1 and -2 were collocated at Wettzell.

5. The WEGENER Medlas Program was started with measurements in Switzerland and Italy, but measurements in Greece and Turkey were delayed by the upgrade of TLRS-1.

6. LLR, celebrating its fifteenth year, received a new impetus with successful lunar ranging from MLRS; Haleakala, Hawaii; and Grasse, France.

7. An agreement was drafted with Saudi Arabia for SLR/VLBI cooperation.

8. Transfer of Mobile VLBI operations to NOAA was completed with transfer of MV-1 and MV-2.

9. A Notice for Crustal Dynamics Research was issued and 44 investigations were selected.

10. A second set of Interagency GPS tests were conducted.

11. A Gravity Gradiometer Study Team was formed under the direction of MSFC; and work was started on planning for a SGG Experiment.

12. Conversion of Geodyn-II and Solve to the Cyber 205 was completed; and development of a data set for GRM processing methods simulation tests was started.

13. A report on the GRM Science Conference was published (NASA, 1985b).

E. 1986

1. A third set of measurements was obtained by MV-2 and -3 in Alaska.

2. Moblas-1 in French Polynesia was decommissioned to be replaced by TLRS-2; Moblas-2 was dedicated at Bar Giyyora, Israel; and Moblas-3 was mothballed.

3. Moblas-7 operations with MCP photomultiplier tubes and Tennelec discriminators resulted in single shot precisions of seven millimeters.

4. The Japanese "Ajisai" Satellite (EGP) was launched and was tracked by the global laser network.

5. A proposal to study relativity by changing the proposed orbital inclination of Lageos-II so that the orbital plane would be perpendicular to the orbital plane of Lageos-I was placed under review; an alternative proposal was to build a third Lageos for this purpose.

6. A new narrow-track head for the Mark III DAT tape recorder reduced the number of tapes required for a 24 hour observation period from 24 to 2.

7. Tests of the new "J-series" Water Vapor Radiometer (WVR) were begun.

8. The Washington VLBI correlator was dedicated.

9. The USNO and the NGS concluded an agreement for establishment of the NEOS using VLBI.

10. IAU Symposium No. 128, "Earth Rotation and Reference Frames for Geodesy and Geodynamics" was held October 20-24, 1986 at Coolfont, West Virginia. A variety of topics were discussed, including the LOD-atmospheric angular momentum correlation and the VLBI solutions for nutations using the POLARIS/IRIS Network.

11. A multi-group measurement campaign was organized for southern California to continue the validation and intercomparison of GPS receivers and to begin densification of crustal strain mapping.

12. The first GPS measurements were made in the Caribbean and included baselines between Grand Turk, Dominican Republic, Puerto Rico, and Guantanamo Bay (Cuba).

13. A joint NASA/CNES study was initiated on the feasibility of a Magnolia/MFE mission for long-term measurements of the main magnetic field.

14. A joint NASA/ESA study was initiated on the feasibility of combining the American GRM with the German POPSAT and the French GRADIO.

15. TOPEX was approved by the U.S. Congress as a new start for fiscal year 1987.

16. A draft report of the Geophysics Panel of the ESSC was issued.

F. 1987

1. Analysis of data from 23 experiments using Pacific and North American VLBI stations indicated current relative motion is not significantly different from the Minster-Jordan RM2 model.

2. TLRS's returned to the field: TLRS-1 joined MTLRS-1 and -2 in Turkey and Greece as part of the WEGENER Medlas Project and visited six sites; TLRS-2 replaced Moblas-1 in French Polynesia; TLRS-3 and -4 completed system integration and began collocation tests.

3. The upgrade of Moblas-4 through -8 with MCP PMT's and Tennelec discriminators was completed, resulting in subcentimeter single-shot (rms) precisions.

4. PSN/NASA prepared a joint Lageos-II Research Announcement for investigator

proposals.

5. A decision was made to proceed with plans to relocate the MLRS to a site with improved seeing conditions.

6. The Operation Readiness Review for the NLRS was held.

7. Laser Data Analysis Centers adopted a new SLR data format (MERIT-II) which provided for the higher accuracy (millimeter) laser data which would be produced.

8. The fourth Alaskan campaign was conducted: budget reductions limited observations to the use of only one mobile VLBI station.

9. MV-3 was used by NGS on a reimbursable basis to obtain measurements for four sites of the NCMN and to obtain measurements in Bermuda as part of the NOAA Global Sea Level Program.

10. USNO and NRL were approved to use the NASA VLBI Station at Fairbanks, Alaska, once per week, on a reimbursable basis, for an experiment on forecasting polar motion and Earth rotation.

11. A VLBI workshop was held at the NASA Wallops Flight Facility to examine error sources and to evaluate the feasibility of using phase connection between antennas; installation of a HEMT in VLBI receivers was shown to decrease system noise by 30-40%.

12. The Italian VLBI Station at Medicina (near Bologna) became operational and, through agreement, began observations with IRIS.

13. The IERS was approved by the IAU and IUGG as the new international service beginning in 1988.

14. IAU Symposium #129, The Impact of VLBI on Astrophysics and Geophysics, was held in Cambridge, Massachusetts.

15. Plans were made for a GPS campaign in early 1988 involving several U.S. and European groups for initial surveys in Columbia, Costa Rica, Venezuela, and Ecuador; the second GPS Technology Workshop was held at JPL.

16. The Magnolia/MFE Phase A study was completed, and the Phase B study started.

17. Investigators were selected for the NASA/PSN TSS experiments: included was a magnetometer proposed by a joint Italian/U.S. team.

18. NASA decided to discontinue all work on GRM.

19. NASA and ESA concluded that a combined GRM/POPSAT/GRADIO mission would be too costly, and agreed to consider a joint mission based on GRADIO, a double-DISCO, a magnetometer, and GPS tracking.

20. The GEM-T1 gravity field model (degree and order 36) was developed.

21. A Workshop was held at Colorado Springs, Colorado, to define requirements for gravity field measurements through the next decade (NASA, 1987).

APPENDIX A

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AAM	Atmospheric Angular Momentum
AFGL	Air Force Geophysics Laboratory
AGU	American Geophysical Union
ALSEP	Apollo Lunar Science Experiment Package
AM0-2	Tectonic Plate Model (Minster and Jordan)
ANNA	Army-Navy-NASA-Air Force satellite
AO	Announcement of Opportunity
APL	Applied Physics Laboratory
ASTP	Apollo-Soyuz Test Program
ATS	Applications Tecnnology Satellite
BIH	Bureau International de l'Heure
CALC	Computer program for VLBI solutions
CDP	Crustal Dynamics Project
CIT	California Institute of Technology
cm	Centimeter
CMB	Core Mantle Boundary
CNES	Centre Nationale d'Etudes Spatiales (France)
COSMOS	USSR Satellites
COTES	Joint Working Group on the Establishment and Maintenance of a Conventional Terrestrial Reference System
CSTG	Commission for Coordination of Space Techniques for Geodesy and Geodynamics
DATS	Data Acquisition Terminal (VLBI)
DE	Dynamics Explorer (Satellite)
DIS	Data Information System
DISCOS	Disturbance Compensation System
DMA	Defense Mapping Agency
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
DOI	Department of Interior
DSN	Deep Space Network
E	Eövo"s Unit (10^{-9} sec^{-2})
ECMWF	European Centre for Medium-Range Weather Forecasting
EGP	Experimental Geodetic Payload (Japan)
EOPAP	Earth and Ocean Physics Application Program
Eos	Earth Observing System
ERBE	Earth Radiation Budget Experiment
ERL	Environmental Research Laboratory (U.S. Army)
ERS	ESA Remote Sensing Satellite
ERS-1	Earth Resources Satellite (Japan)
ESA	European Space Agency
ESSC	Earth System Sciences Committee
FET	Field Effect Transistor
FCN	Fluid Core Nutation
FRG	Federal Republic of Germany
GAPE	Great Atlantic and Pacific Experiment
GEM	Goddard Earth Model

GEODYN	Goddard Computer Program for Geodynamics and Orbital Computations
GEOS	Geodynamic Experimental Ocean Satellite (formerly Geodetic Satellite)
GHz	10^9 Hertz
GIPSY	GPS Inferred Positioning System
GLOBL	Computer program for global solutions
GM	Product of the gravitational constant and the mass of the Earth
GPS	Global Positioning System
GRADIO	Gravity Gradiometer (France)
Gravsat	Gravity Field Satellite (Changed to GRM)
GRL	Geophysical Research Letters
GRM	Geopotential Research Mission
GRMSSG	GRM Science Steering Group
GSFC	Goddard Space Flight Center
GLRS	Geodynamics Laser Ranging System
GSPB	Geodetic Satellite Program Board
HEMT	High Electron Mobility Transistor
Hz	Frequency in cycles per second
HRAS	Harvard Radio Astromony Station
IAG	International Association of Geodesy
IAGA	International Association of Geomagnetism and Aeronomy
IASOM	Institute for Advanced Study in Orbital Mechanics (UTX)
IAU	International Astronomical Union
ICCG	Interagency Coordinating Committee for Geodynamics
ICSU	International Council of Scientific Unions
IERS	International Earth Rotation Service
IF	Intermediate Frequency
IfAG	Institut fu "r Angewandte Geodä'sie (Germany)
IGRF	International Geomagnetic Reference Field
ILP	International Lithosphere Program
ILS	International Latitude Service
IPMS	International Polar Motion Service
IRIS	Italian Research Interim Stage (Italy)
IRIS	International Radio Interferometric Surveying (U.S.)
IUGG	International Union of Geodesy and Geophysics
IWGMFS	International Working Group on Magnetic Field Satellites
J_2	Gravity field zonal harmonic
JGR	Journal of Geophysical Research
JMA	Japanese Meteorological Agency
JPL	Jet Propulsion Laboratory
km	Kilometer
Lageos-I	Laser Geodynamics Satellite (U.S.)
Lageos-II	Laser Geodynamics Satellite (Italy)
Laser	Light Amplification By Stimulated Emission of Radiation
LASSO	Laser Synchronization from Stationary Orbit
LLR	Lunar Laser Ranging
LOD	Length of Day
LURE	Lunar Ranging Experiment (Apollo)
Ma	Million years
Magnolia	Magnetic Field Satellite (France)
Magsat	Magnetic Field Satellite (U.S.)

mas	Milliarcsecond
MCP	MicroChannel Plate (photomultiplier)
Medlas	Mediterrean Laser Project (WEGENER)
MERIT	Monitor Earth Rotation and Intercompare Techniques
MFE	Magnetic Field Explorer (U.S.)
mgal	Milligal (10^{-3} cm sec^{-2}, approximately 10^{-6} g)
mj	Millijoule
MLRS	McDonald Laser Ranging Station
mm	Millimeter
Moblas	Mobile Laser
MPIfRA	Max Planck Institute for Radio Astronomy
mrad	Milliradian
ms	Millisecond
MSFC	Marshall Space Flight Center
MTLRS	Modular Transportable Laser Ranging System
MV	Mobile VLBI
NAS	National Academy of Science
NASA	National Aeronautics and Space Administration
Natmap	Division of National Mapping (now Survey Mapping Group of Australian Survey Office)
NBS	National Bureau of Standards
NCMN	National Crustal Motion Network (NOAA)
Nd:YAG	Neodymium:Yttrium/Aluminum/Garnet (type of laser crystal)
NEOS	National Earth Orientation Service (U.S.)
NGS	National Geodetic Survey
NGSP	National Geodetic Satellite Program
NLRS	Natmap Laser Ranging Station (Australia)
nm	nanometer
NMC	National Meteorological Center (U.S.)
NOAA	National Oceanic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NRL	Naval Research Laboratory
NROSS	Navy Research Oceanographic Satellite System
ns	Nanosecond
NSF	National Science Foundation
nT	NanoTesla
NUVEL-1	Tectonic Plate Model (deMets)
OASIS	Orbiter Analysis and Simulation Software
OGO	Orbiting Geophysical Observatory
OSSA	Office of Space Science and Applications (NASA)
OVRO	Owens Valley Radio Observatory
PMT	PhotoMultiplier Tube
PPME	Pacific Plate Motion Experiment
POGO	Polar Orbiting Geophysical Observatory
POLARIS	Polar Motion Analysis by Radio Interferometric Surveying
POPSAT	Precise Orbiting Positioning Satellite (ESA)
ppm	Parts per million
pps	Pulses per second
ps	Picosecond
PSN	Piano Spaziale Nazionale (Italy)
RGO	Royal Greenwich Observatory

rms	Root mean square
RRL	Radio Research Laboratory (Japan)
SAFE	San Andreas Fault Experiment
SAO	Smithsonian Astrophysical Observatory
Seasat	Ocean Dynamics Monitoring Satellite
SERIES	Satellite Emission Radio Inferred Earth Surveying
SGAB	Satellite Geodesy Applications Board
SGG	Superconducting Gravity Gradiometer
SGGM	Superconducting Gravity Gradiometer Mission
SLR	Satellite Laser Ranging
SLRS	Spaceborne Laser Ranging System
SOI	Southern Oscillation Index
SOLVE	Goddard computer program for solving normal equations
SPAN	Space Physics Analysis Network
Spartan	Reuseable Shuttle subsatellite
SST	Satellite-to-Satellite Tracking
Stalas	Stationary Laser Station (GSFC)
Starlette	Satellite equipped with cube corner retroreflectors (France)
STDN	Space Tracking and Data Network
TLRS	Transportable Laser Ranging Station
TOPEX	Ocean Topography Experiment
TSS	Tethered Satellite System
UCB	University of California at Berkeley
UCLA	University of California - Los Angeles
UMD	University of Maryland
USGS	United States Geological Survey
USNO	U.S. Naval Observatory
UT1	Universal Time
UTX	University of Texas (at Austin)
VLBA	Very Long Baseline Array
VLBI	Very Long Baseline Interferometry
VLSI	Very Large Scale Integrated Circuitry
WEGENER	Working Group of European Geo-Scientists for the Establishment of Networks for Earthquake Research
Wettzell	Laser and VLBI Station (Federal Republic of Germany)
WVR	Water Vapor Radiometer

APPENDIX B

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